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THE HIGH SPEED WATER TUNNEL
THREE-COMPONENT FORCE BALANCE

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Approved by:
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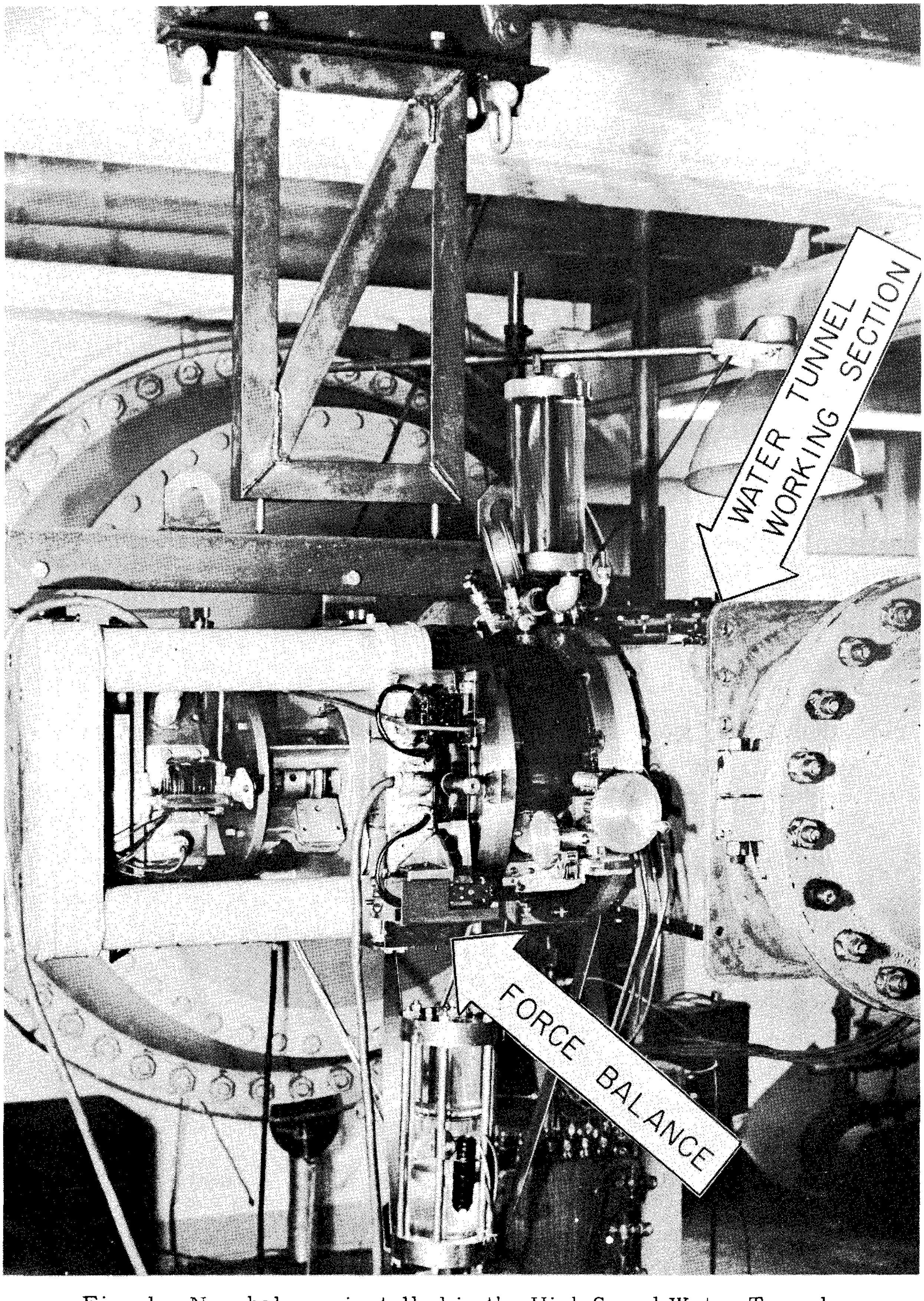

Fig. 1 - New balance installed in the High Speed Water Tunnel for hydrofoil force measurements.

ABSTRACT

An experimental program was initiated in the High Speed Water Tunnel to measure force coefficients for hydrofoils under cavitating conditions. This program necessitated either a new force balance or a major modification of the existing one. Various balance configurations and pressure seal designs which were considered are described. A balance modification design was selected which consists of an appendage bolted between the existing balance and the water tunnel working section. This appendage alters the basic geometry of the force balance so that the model is now mounted on a parallelogram linkage instead of on a simple pivoted lever. The addition of the parallelogram force table suspension to the old balance renders the modified balance unresponsive to moments which, in the old balance, interacted with forces, and resulted in errors in the force readings. This modification which is described in detail was accomplished and resulted in a successful force balance capable of accurate measurement of forces on cavitating and noncavitating hydrofoils; and, in fact, it is expected to replace the old force balance for all force measurement work in the High Speed Water Tunnel. The cost and construction time for the balance modification were considerably less than would have been required for an entirely new force balance of comparable accuracy and sensitivity.

I. INTRODUCTION

The measurement of hydrodynamic forces on underwater bodies is one of the principal uses for water tunnels. For this type of work an accurate force balance is necessary. Water tunnel force measurement work closely resembles wind tunnel test work and, in fact, the types of force balances may be similar. Balances for the two types of tunnels differ mainly in the severe requirements of the pressure seal in the water tunnel balance. Water tunnels used for cavitation work are, at times, operated at pressures of about 100 pounds per square inch, resulting in the introduction of very large axial forces, of the order of 500 to 1000 pounds, into the balance by the pressure seal. Yet the seal must be so designed or located as not to introduce a force greater than 1/100,000 of this axial force into the force measuring system.

A successful force balance has been in operation in the High Speed Water Tunnel of the Hydrodynamics Laboratory for the past 13 years. It is an external type three-component balance with hydraulic force sensing elements and automatic weighing type pressure gages for read out. The accuracy of force measurements made with this balance has recently been improved through the addition of an internal moment measuring balance, i.e. one within the model. The combination of these two units has provided a force balance which has proved highly satisfactory for the measurement of forces on axially symmetrical bodies.

An experimental program has recently been initiated in the High Speed Water Tunnel to measure force coefficients on two- and three-dimensional hydrofoils where space for an internal moment measuring balance is not available. This program necessitated, therefore, either a new force balance or a major modification of the existing one.

Design studies undertaken to determine the most expedient means of obtaining a suitable force balance for the hydrofoil program led to the conclusion that an appendage to the old balance which would eliminate the need for a moment measuring balance by "grounding" these moments appeared most promising and it was therefore built. The modified balance has performed satisfactorily on hydrofoil studies conducted to date.

Since other laboratories are known to be interested in water tunnel balances for force measurement work, it was felt that experience gained in the design studies and construction of the High Speed Water Tunnel force balance might prove of some value. The purpose of this report, therefore, is to describe the modification to the balance and to outline the balance and pressure seal design studies in some detail.

II. THE ORIGINAL BALANCE

A. Description of Original Force Balance

The three-component force measuring balance* used in the High Speed Water Tunnel, Hydrodynamics Laboratory, is a device which measures the hydrodynamic forces on a model mounted on a spindle in the 14" diameter working section of this tunnel (see Figs. 2 and 3). The balance consists of a vertical spindle supported near the center with a universal pivot which permits rotation about any axis through this point but no translation. The model is attached rigidly to the top of the spindle. This assembly is prevented from rotating under the action of the hydrodynamic forces by applying restraining moments about three mutually perpendicular axes intersecting at the pivot. These moments are applied by hydraulic pressures through three sets of pistons, cylinders and yoke wires. The three restraining moments measure the components of the hydrodynamic forces acting on the model as hydraulic pressures, which are read out on three automatic weighing type pressure gages.

A pressure seal** consisting of a molded neoprene tube with metal ring reinforcements is employed and is attached to the spindle close to the universal

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*The High Speed Water Tunnel at the California Institute of Technology, by R.T. Knapp, V.A. Vanoni and J.W. Daily, HML Report No. ND-1, June 29, 1942; and The Hydrodynamics Laboratory of the California Institute of Technology, by R.T. Knapp, Joseph Levy, J.P. O'Neill and F.B. Brown, Trans. of the A.S.M.E., July 1948.

**See Appendix II C 1 for description of this seal.

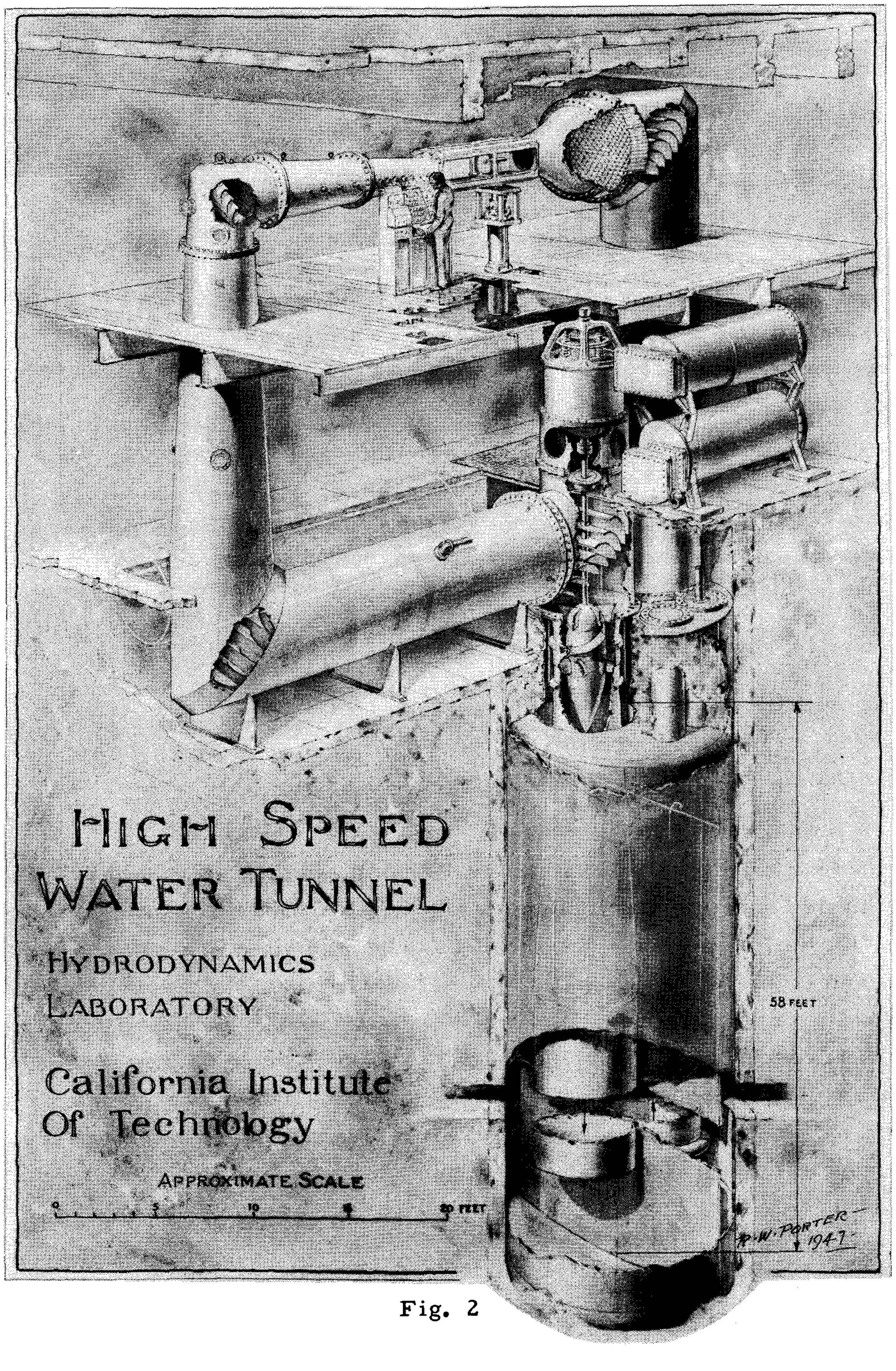
HIGH SPEED
WATER TUNNEL
HYDRODYNAMICS
LABORATORY
California Institute
Of Technology
APPROXIMATE SCALE
0
5
10
15
20 FEET
58 FEET
P.W. PORTER
1947

Fig. 2

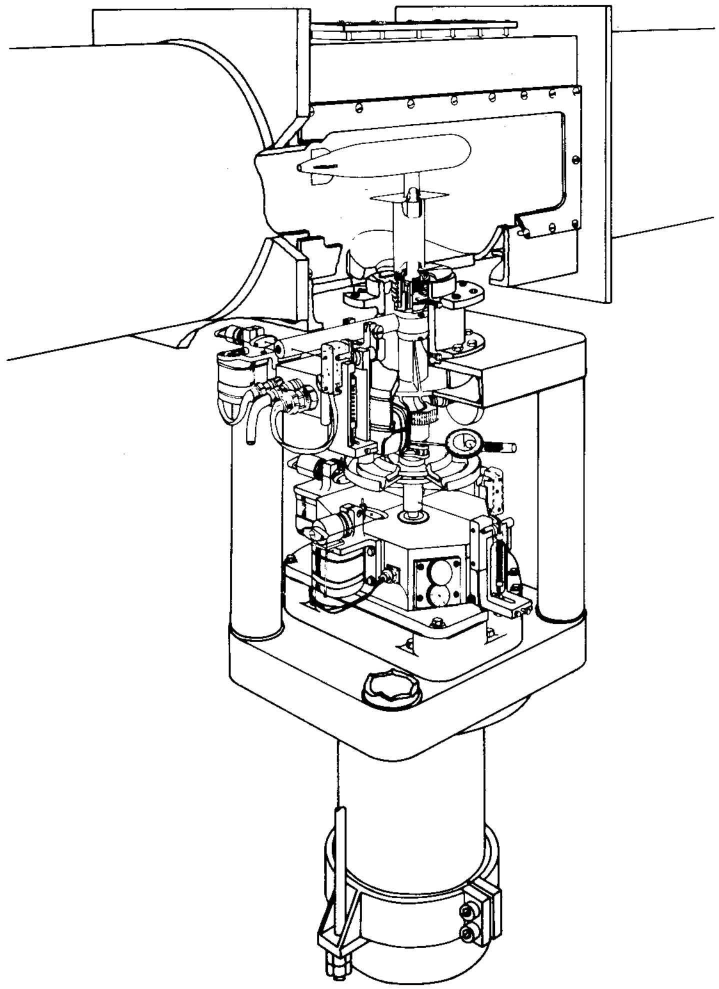

Fig. 3 - The original force balance.

pivot center so that any components of the large axial pressure force which might affect the drag* or lift readings are effectively grounded. Figure 4 is a schematic diagram of the balance system, force transmitting system and pressure gage used to measure drag force; similar systems are used to measure lift and pitching moment. The hydrodynamic force on the model is transmitted to the restraining wire at the bottom of the lower spindle. The wire and yoke transfer the force to the hydraulic piston. In order to measure positive and negative forces with one piston, a spring preloader is used. To eliminate static friction, the hydraulic cylinders are rotated by individual motors.

The pressures in the cylinders on the balance are measured by weighing-type pressure gages, as shown schematically in Fig. 4. The gage consists essentially of a beam supported on a Cardan hinge pivot. The pressure to be measured is applied to a piston attached to this beam, through another flexural pivot, the piston being fitted in a cylinder which is rotated to avoid static friction, the same as in the case of the balance pistons and cylinders. The force exerted by the oil pressure on the piston is balanced by pan weights applied to the end of the beam and also by a rider weight running on the beam. Unbalance of this beam results in unbalance of the electrical control system which, in turn, automatically

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*See Appendix I for definition of forces and moments.

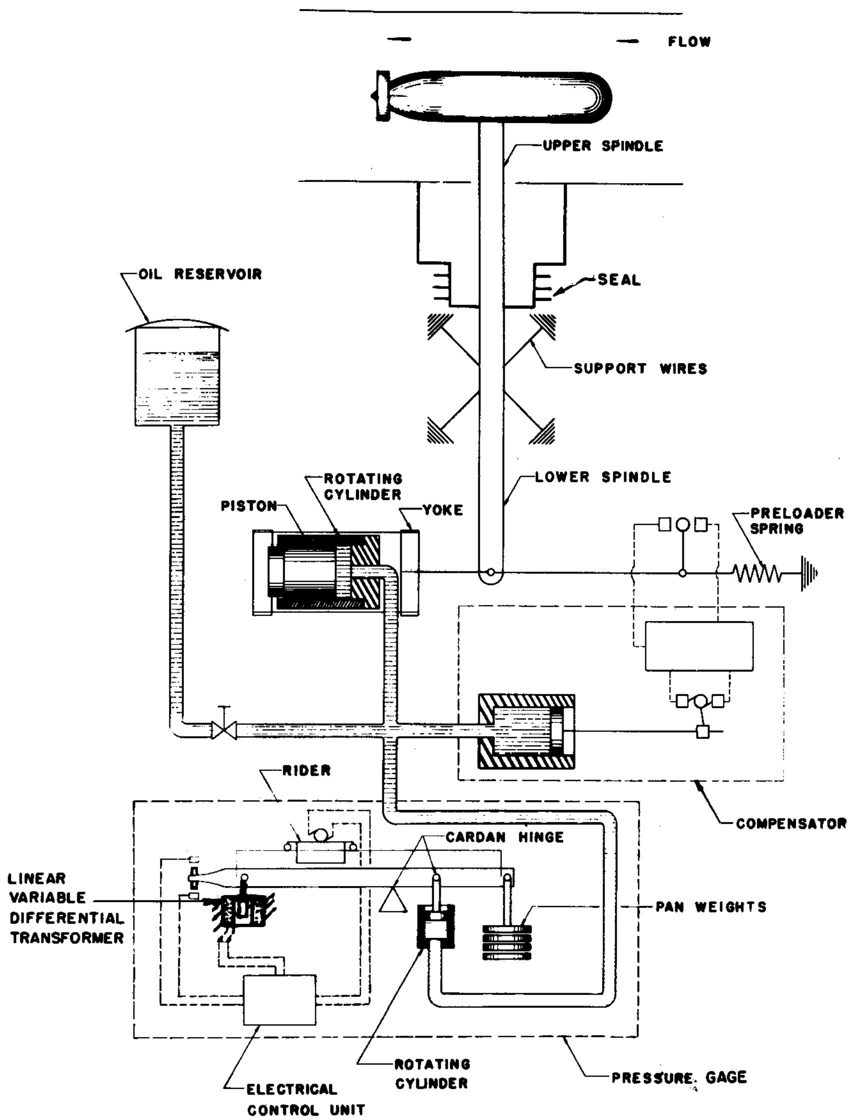

Fig. 4 - Schematic of the original force measuring system.

moves the rider weight until equilibrium is obtained. The position of the rider is indicated by a counter which reads directly in pounds of force to the nearest 0.01 pound (or inch pounds of moment to the nearest 0.01 inch pound).

B. Geometry of Original Balance

As previously noted, the original three-component force measuring balance (see Figs. 5 and 18) measures drag, lift and pitching moment as moments about the universal pivot center. Thus a drag force F_{Drag}, in Fig. 5, produces a moment $F_{Drag} \times \ell_1$ about the pivot center and a force on the drag piston of $F_{Drag} \times \ell_1/\ell_2$, which is in turn read out as a pressure p_d equal to $F_{Drag} \times \ell_1/\ell_2 \times A_{piston}$. Values of drag and lift measured by this balance are correct for axially symmetrical (torpedo-like) bodies where the sum of all yawing and rolling moments about the design model force center (point A, Fig. 5) is zero.

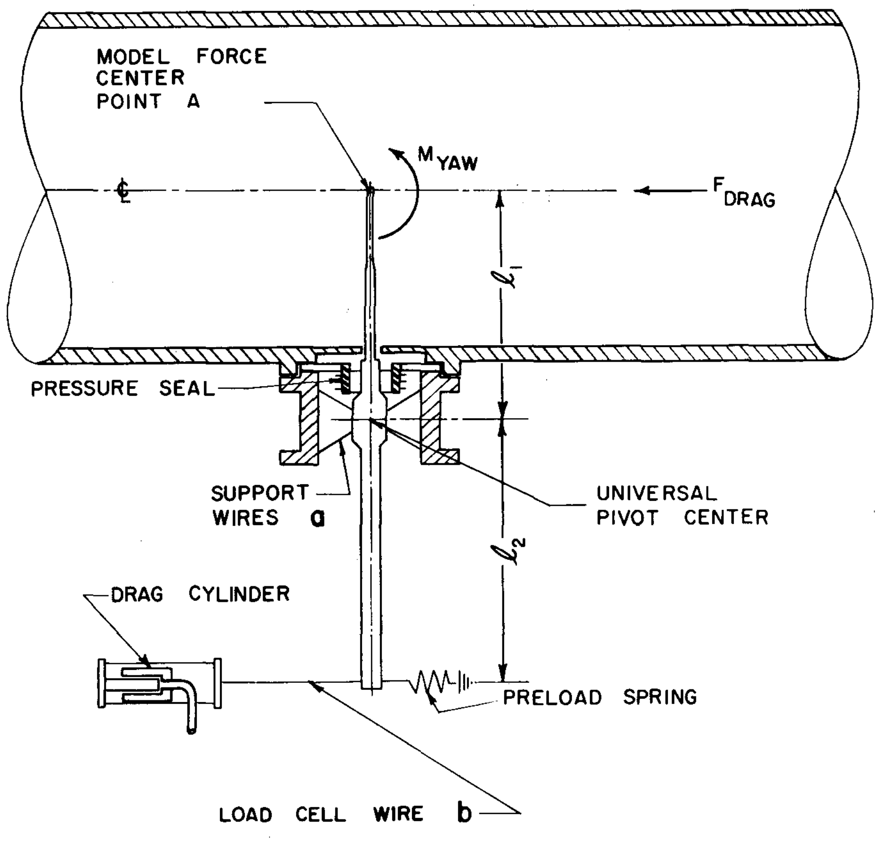

Fig. 5 - Schematic showing interaction of yawing moment with drag force in original balance.

C. Unsuitability of Original Balance for Hydrofoil Studies

If, however, moments about the model force center do exist, for example a moment M_{yaw}, (Fig. 5), a force M_{yaw}/ℓ_2 will be applied to the drag piston which will erroneously be read out as additional drag. Significant yawing moments may result from nonuniformities in flow past the model due to: (1) irregularities in tunnel flow, (2) shield interferences, (3) inclination of model as a result of mechanical deflections, (4) unsymmetrical model. For bodies of ample size (approximately 1 inch minimum dimension) errors in drag reading due to the interaction of yawing moment with drag can be corrected through the use of an internal balance for measuring yawing moments. Such balances have been built for use with 2" diameter torpedo-like models and are considered an essential adjunct to the old force balance for force measurements on axially symmetrical bodies. Rolling moments, if significant, could be measured and corrections made to lift forces in a similar manner.

In the case of hydrofoils, such moment measuring balances would be impractical as the thickness of models is on the order of 1/4"-3/8" which does not provide space enough for a moment balance of adequate rigidity. Rolling and yawing moments were expected with two-dimensional hydrofoils due to flow disturbances resulting from (1) irregularities in tunnel flow, (2) differences in tip disturbances at the two ends because of flow through hydrofoil hub clearance. Since drag forces acting on two-dimensional hydrofoils are small compared to lift forces, large percentage errors in drag readings might be introduced by yawing moment interactions. For three-dimensional hydrofoils, large rolling and yawing moments would be expected due to the considerable displacement of the lift and drag centers from the model force center, Point A, Fig. 5.

Past experience has also indicated that the original force balance required greater stiffness, mass, or damping for measuring forces on cavitating bodies as the variation in forces is of such magnitude as to cause the compensators, see Fig. 4, to operate more or less continuously and pressures read out by the pressure gages are not correct when the compensators are operating.

In view of the foregoing, it was concluded that a new force balance or a major modification of the existing one was necessary to eliminate the effects of moment interactions on the measurement of hydrodynamic forces on hydrofoils.

III. SCOPE OF DESIGN STUDIES AND DEVELOPMENT ON NEW BALANCE

As it appeared that any modification which would make the original balance suitable for use in the hydrofoil studies would be a major one, it was decided to investigate construction of an entirely new balance as well. In a new balance it would also be possible to eliminate some of the minor defects in the existing balance. Preliminary studies of new balances and modifications of the old balance were undertaken with a view toward either eliminating yawing and rolling moments from the weighing system or measuring and correcting for them. The following were among arrangements considered:

A. New balances:
  (1) Pyramidal type six-component balance;
  (2) Parallelogram type* three-component balance.

B. Modification of existing balance:
  (1) Strut type model mount with force cells to measure yawing and rolling moments;
  (2) Parallelogram mounted force table appendage to "ground" yawing and rolling moments.

As previously mentioned the pressure seal employed in the old balance was satisfactory with this balance since the seal could be attached to the spindle close to the fulcrum point, thereby preventing any spurious seal forces from entering the weighing system. In the case of the two new balance designs the use of the original balance seal was not feasible since the seal would have to be attached, in effect, directly to the force table, resulting in direct reading of these large spurious seal forces. Consequently, studies were also made of new sealing arrangements. Discussion of seal designs together with balance designs considered is included in Appendix II. Description of the force balance design modification actually adopted follows in paragraph IV C below.

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*Force table mounted as movable top link of a four bar linkage, bottom link fixed.

IV. MODIFIED FORCE BALANCE DESIGN SELECTED FOR HYDROFOIL PROGRAM

A. Advantages of Design

The preliminary design studies of new force balances indicated that construction of such balances would be considerably more expensive both in money and time than construction of one of the balance modification designs studied. This modification, shown schematically in Fig. 6, consisted of the addition of a parallelogram mounted force table to the present balance, thus combining the advantages of the parallelogram force table

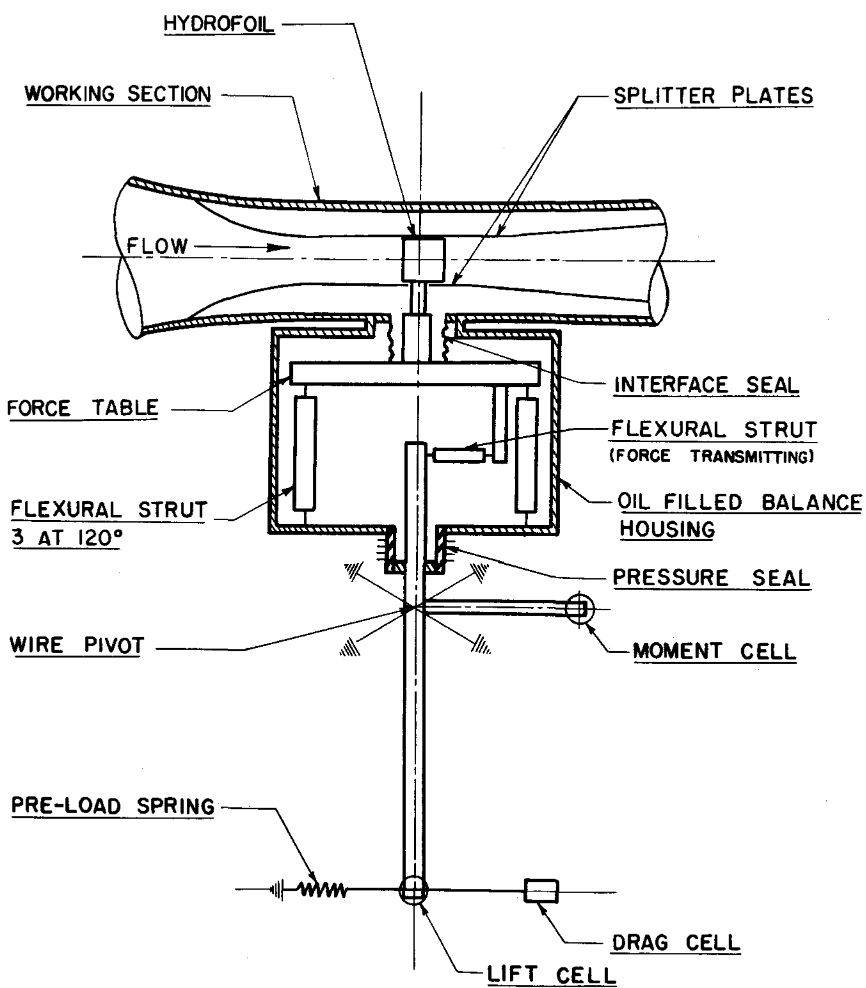

Fig. 6 - Schematic of three-component force balance as modified for hydrofoil program.

suspension of new balance designs and the simplified pressure seal of the original balance. It may be seen in Fig. 6 that yawing and rolling moments applied to the force table by the model are "grounded" by the vertical flexural struts and that pressure seal forces are largely grounded by the universal wire pivot. Further advantages were:

(1) The old balance could be retained intact with the exception of the model pitching apparatus which would merely be disconnected. Hence the old balance arrangement could always be restored.

(2) The new force table appendage could be built and assembled while the old balance was still in use. The old balance would not be needed until the assembly was complete and ready for adjustment.

(3) The new appendage was relatively simple, would not require the construction of any new hydraulic load cells or an unproved sealing arrangement and could be built in a shorter time and at less cost than an entirely new balance.

B. Balance Modification Design Requirements

In view of the foregoing, a detailed design of the proposed new force table appendage was started, based upon the following premises:

(1) The modified balance was intended for side mounting (working section to be rotated 90°) for the hydrofoil program to prevent having a spanwise static pressure variation on the hydrofoils, but was to be suitable for standard vertical mounting off the floor as well.

(2) The old balance was to remain essentially unaltered so that in the event the new balance did not prove superior for all conditions, the old balance could still be used. This requirement dictated that the flexural struts and interface seal in the new force table appendage be so "soft" as not to affect the least count of the balance.

(3) Design loads were:

Lift	+ 150 lb - 50 lb	Drag	+ 50 lb - 50 lb
Moment	$\pm$ 200 in. -lb		

For simplicity of fabrication, thicknesses of all force-transmitting strut flexures were made the same, so that the actual load-carrying capacity of these elements is:

Lift	+ 150 lb - 150 lb	Drag	+ 150 lb - 150 lb
Moment	+ 560 in. -lb - 560 in. -lb		

The above loads cannot be applied simultaneously, as the force table struts were designed for simultaneous application of the lower loads specified under "design loads".

(4) Since the balance was to be used to measure forces on cavitating hydrofoils which would produce large lift forces of a vibratory nature, every effort was to be made to stiffen the balance. This was to be accomplished by:

(a) Making the new force table very rigid and providing a generous "wheelbase" ;

(b) Employing a very stiff hydrofoil mounting spindle ;

(c) Halving the effective distance between model and balance pivot center from its original figure (i.e., halving ℓ_1 of Fig. 5). This reduction in leverage would:

(i) Reduce sensitivity of the balance by a factor of two ; this was still believed to be ample in view of the very high sensitivity of the hydraulic load cells and pressure gages.

(ii) Increase capacity of the force measuring system by a factor of two ; this was considered of no particular advantage and, since designing the force table appendage to handle such loads would have compromised premise 2 above, it was not done.

(iii) Reduce the deflection of load cell wires, (b) of Fig. 5, and the pressure in the hydraulic system, hence cut the springiness of this system by a half ; reduce deflection of support wires, (a) of Fig. 5, a quarter for the same applied force.

(iv) Decrease the over-all length of the new balance so that it oould be mounted vertically off the floor as required.

The weight of the force table, close-coupled to the hydrofoil, would also serve to reduce much of the unsteadiness of forces introduced into the balance by cavitating hydrofoils.

C. Description of New Force Table Appendage as Constructed

Figure 6 shows the operating principle of the new force table appendage. Three vertical flexural struts support the force table and three force-transmitting flexural struts attach the force table to the spindle of the old balance. Drag, lift and pitching moment are transmitted from the model to the force table, thence to the spindle of the old balance through the force-transmitting struts. Yawing and rolling moments are transmitted to ground through the vertical support struts. Figure 7 shows the new force table mechanism in detail and Fig. 8 shows it assembled on the old balance with the pressure vessel removed. Two of the three vertical flexural support struts may be seen in Fig. 8; flexure thickness for two is 0.005" and is 0.010" for the third; a strut with 0.005" thick flexures is shown in Fig. 9. All struts are made of SAE 4140 alloy steel, heat treated to R_c 35. Sample flexures of the 0.005" thickness were tested in tension to 600 lb (corresponding to an average tensile stress of 145,000 psi) and in compression to 470 lb (corresponding to an average compressive stress of 115,000 psi) where they failed.

The force table proper consists of two very rigid aluminum castings. The hub to which the model spindle is attached is mounted in the top force table casting by means of two large preloaded ball bearings which permit angle of attack of the model to be varied but hold radial deflections under maximum model forces to a very small figure. The force table is in turn attached to the old balance spindle through the three flexural force-transmitting struts, two of which, for convenience, intersect at the balance vertical centerline. The axis of the third strut does not intersect the other two and permits transmission of pitching moment. The entire unit is mounted on a base plate which is, in turn, bolted to the old balance. A cylindrical pressure vessel contains the oil with which the force table appendage is filled and acts as structure to connect the old balance to the working section through a heavy flange.

A worm and worm wheel set is used to change the angle of attack of the model; the worm is rotated by a shaft passing through the pressure vessel to the outside. This shaft has an engage-disengage coupling which is engaged

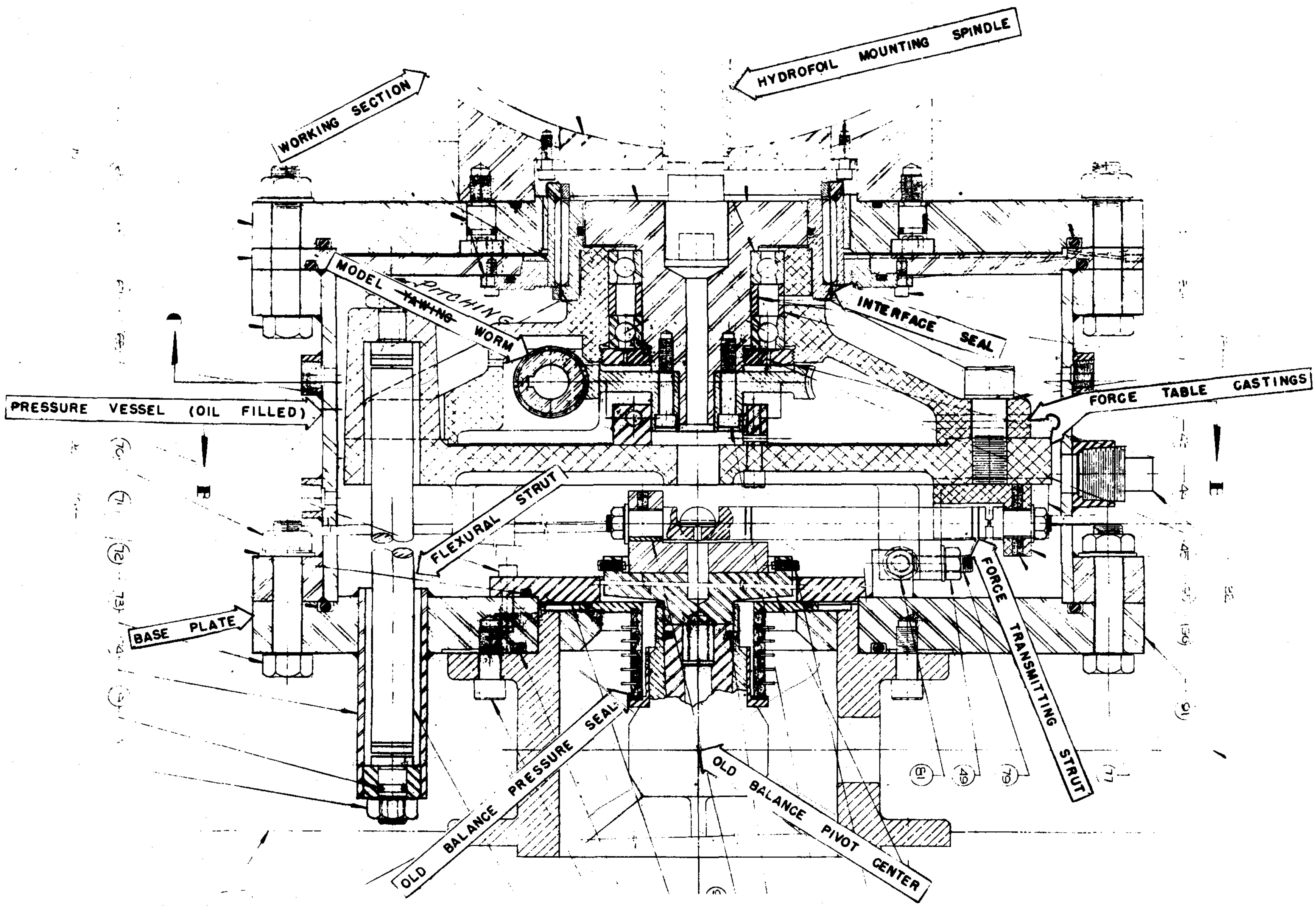

Fig. 7 - Assembly drawing of new force table mechanism.

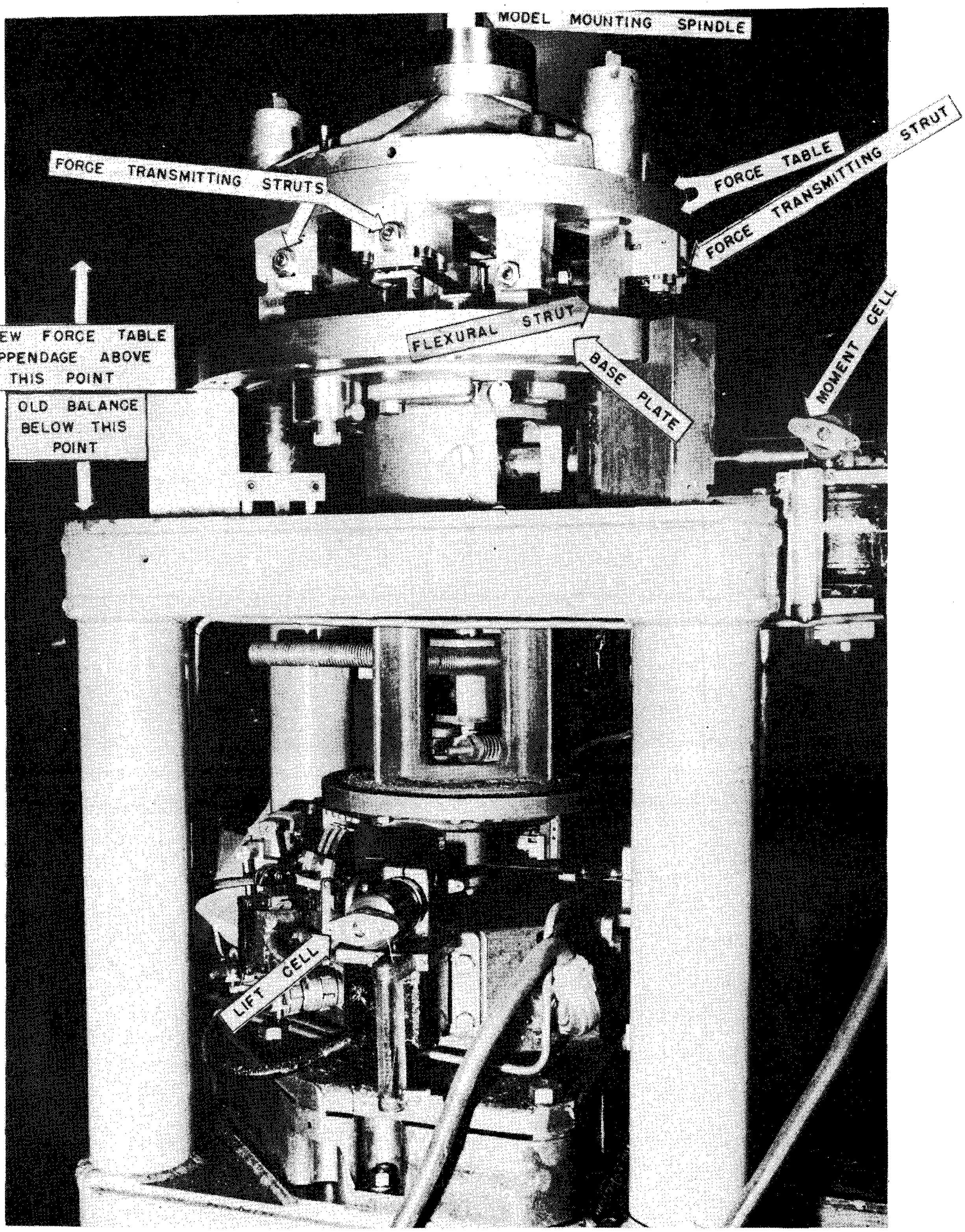

Fig. 8 - New water tunnel force balance.

only when changing the angle of attack. A counter calibrated in degrees and minutes shows the angle of attack of the model. A lock is also provided, operable from an external disengaging shaft, but it has not proved necessary to use it to date as the worm and worm wheel are set up with slight negative backlash. The angle set in the counter is accurate to and will repeat to better than one minute of angle. Adjusting screws are provided to permit alignment of the axes of the new and old balances. Adjustments are provided for the attachment of the three force transmitting flexural struts to the old balance spindle at the proper distance from the wire pivot center.

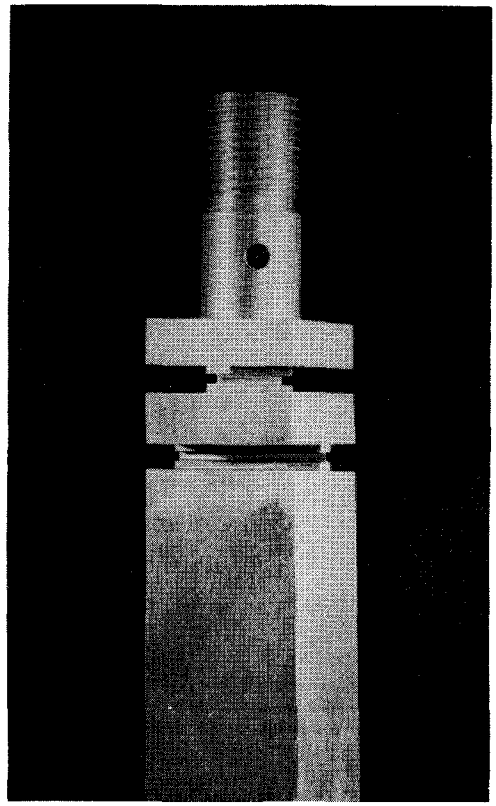

Fig. 9 - Force table support flexural strut. Flexure thickness is .005".

The .015" thick neoprene interface seal which separates the water in the working section from the oil in the balance is installed with small clearances so it cannot be damaged if inadvertently subjected to a differential pressure. An oil-water interface pot is installed in the pressure equalizing line between the working section and the pressure vessel. The oil level is maintained at about mid-height and a float is employed to minimize the area of contact between oil and water, since the presence of water or air in the oil is troublesome when operating the tunnel at low pressures. The interface pot serves several purposes: (a) it provides visual assurance that the interface seal has not broken; (b) should the seal be damaged, it provides an appreciable time interval before water can reach the internal working parts of the balance; (c) when dissolved air or water comes out of the oil at low pressures the pot prevents loss of oil into the working section since as the float level falls water is expelled from the interface pot instead of oil; and (d) if any insoluble gases are trapped in the pressure vessel, the pot prevents the flow of water into the pressure vessel due to compression of these gases at high working section pressures. An oil supply pot is provided at the top of the pressure vessel to prevent the oil level from dropping below the top of the force table as air or oil vapor bubbles evolve and rise at very low tunnel operating pressures, since such a drop in oil level would cause a loss of buoyancy of the force table, hence cause an error in lift reading.

The entire balance is suspended from an overhead trolley which runs on an I-beam to facilitate installing the balance on its side as required for the hydrofoil program; this is shown in Fig. 10. The bulk of the balance weight is carried by the I-beam rather than by the working section.

D. Tests and Calibration

After completion of the new force table assembly it was installed on the old balance, adjusted, and calibrated. Adjustment consisted of: (1) making the axis of the hydrofoil mounting spindle coincident with the vertical axis of the old balance to minimize interactions, and (2) adjusting the distance between the universal pivot center to the attachment point of the force transmitting struts to the proper value to make the force gages read out correctly. Calibration was accomplished using dead weights and reading out on the pressure gages with the balance both upright and on its side. Orientation had no effect other than to change preload values. Next, a pressurizing can, shown in Fig. 11, was installed on top of the balance and calibrations made for all components at various pressures from -10 in. mercury to 60 psi. Change in lift, drag, and moment readings with pressure changes, shown in Fig. 12, correspond almost exactly to those observed with the old balance and are practically independent of load applied. The first two changes can be attributed to noncoincidence of the center of the pressure seal with the axis of the old balance spindle resulting in moments which are read out as lift and drag forces. Variation of moment with pressure is probably due primarily to the universal pivot wires not intersecting at a point. Rolling and yawing moments were applied and were observed to have no effect on the lift, drag, or pitching moment readings.

Figure 15 shows static calibration curves for the new balance operating on its side as required for the hydrofoil program and with the working section filled with water.

E. Operation

The new force balance was first installed in the normal vertical position mounted off the floor as shown in Fig. 13 and the static calibration

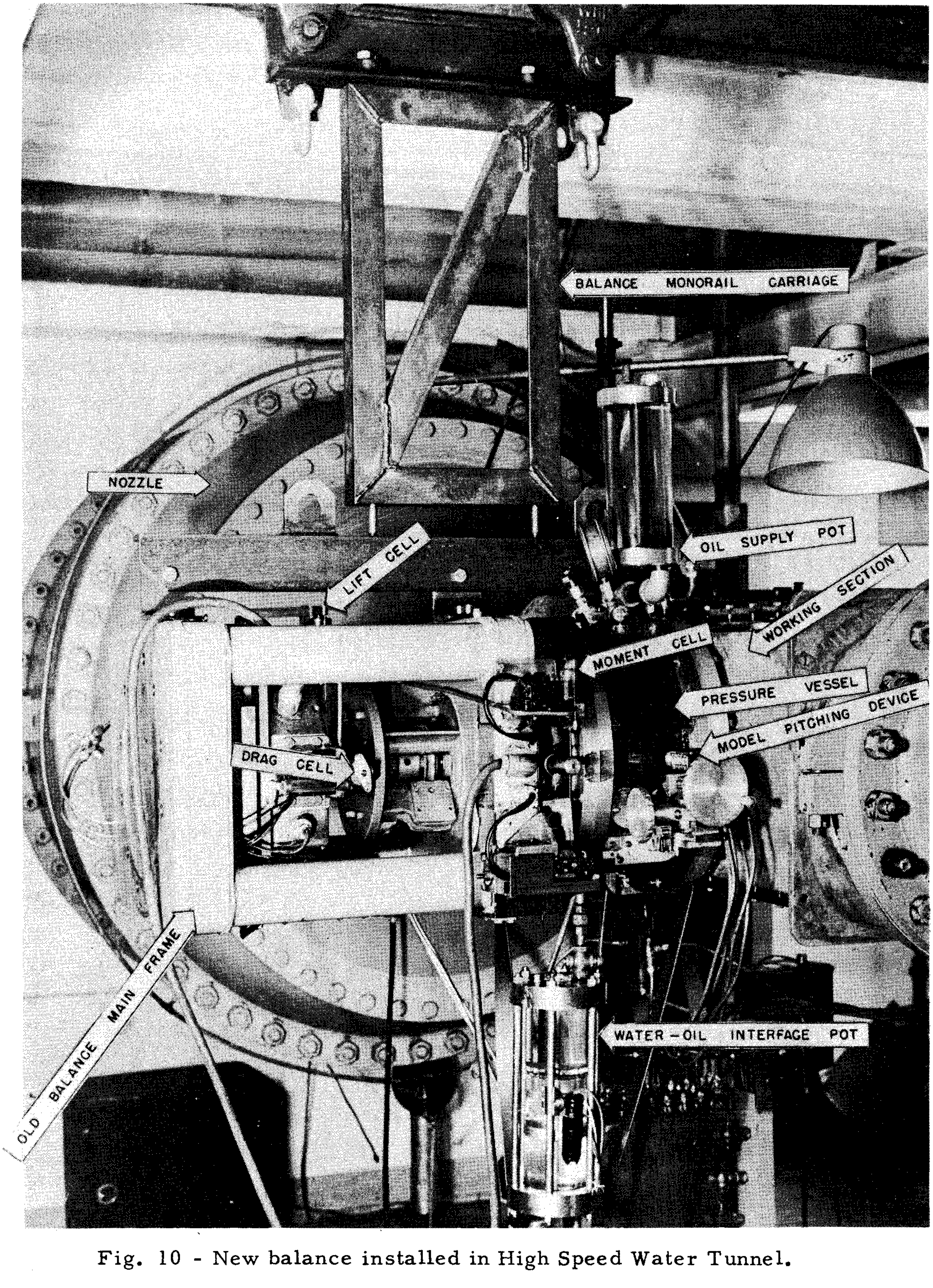

Fig. 10 - New balance installed in High Speed Water Tunnel.

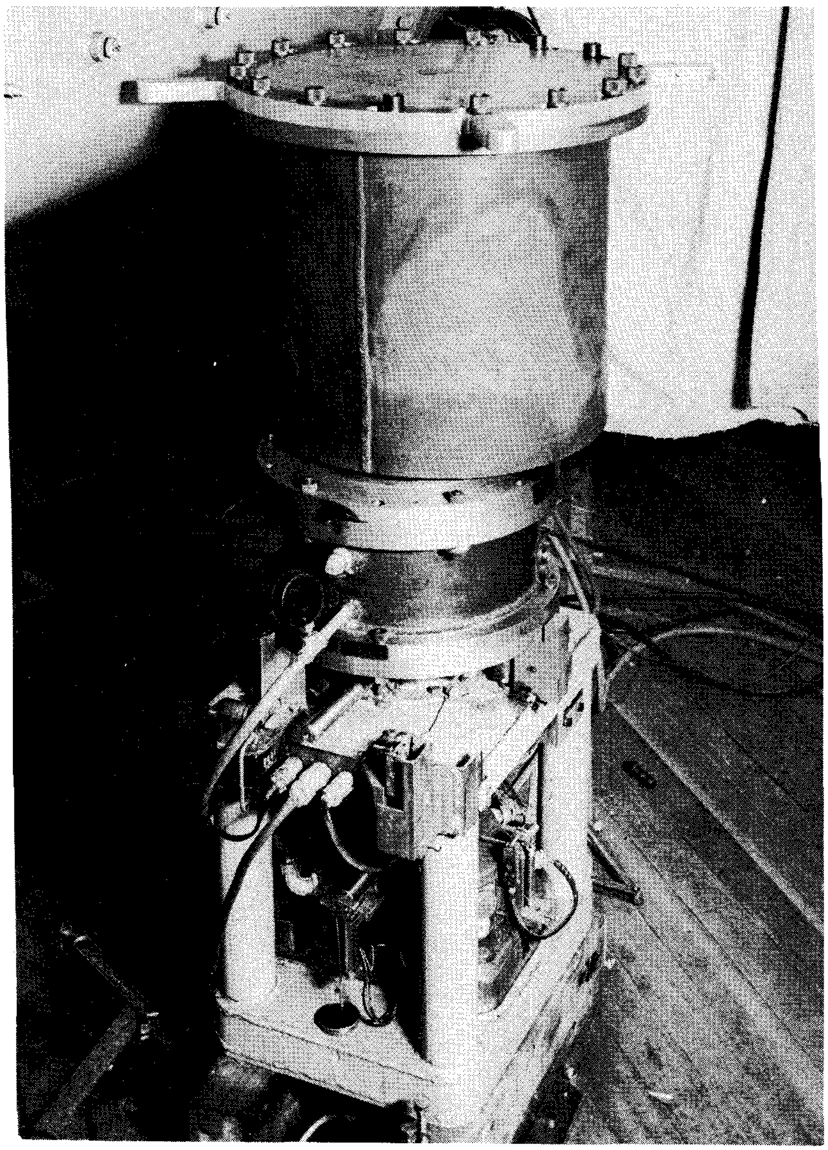

Fig. 11 - Arrangement for calibrating under pressure.

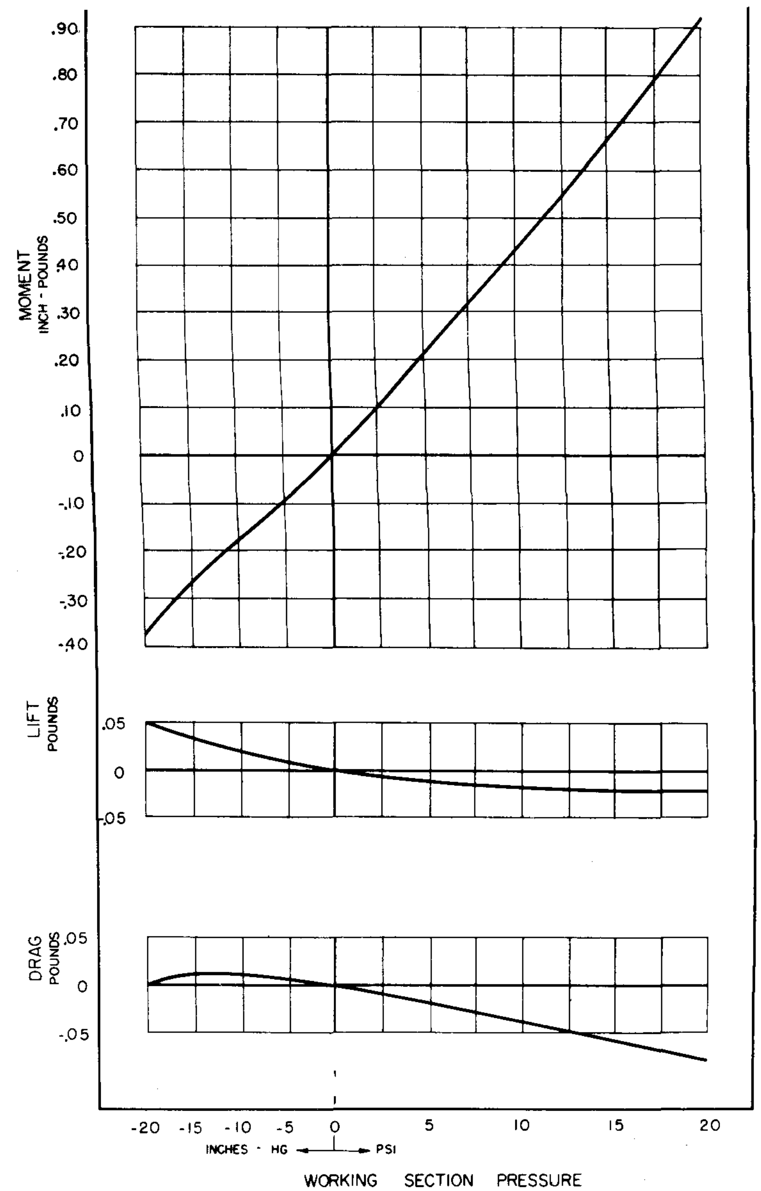

Fig. 12 - Calibration curves for pressure vs. lift, drag, and pitching moment.

rechecked in this position. Operation of the balance with an axially symmetrical model was entirely satisfactory, providing accurate and consistent force measurements.

Next, the working section was rotated 90° and the force balance installed on its side as required for hydrofoil work. Sporadic difficulty was encountered with zero shifts and slight changes in static calibration curves, particularly in the drag component. At times the zero shift amounted to as much as 1 lb of drag; it was finally observed that this shift occurred when working section pressures were changed from positive to negative and vice versa. This led to the discovery that the pressure seal was loose on the spindle of the old balance. When the seal was tightened no further difficulty was encountered with calibration changes or abrupt zero shifts. During subsequent checks to determine that the seal was completely tight, an unexpected hysteresis was observed in all force readings when pressure cycles were repeated several times. As the new interface seal was suspected of being the source of the difficulty, oil was drained from the balance and air pressure applied to both sides of the seal. The scatter in the data was greatly reduced, leading to the conclusion that the difficulty was the result of inadequate bleeding of air from the water side of the interface seal. This was evidently the reason the difficulty did not occur when the balance was operated in the vertical position. Additional bleed holes were provided and the scatter was greatly reduced. Complete bleeding of an interface seal of this type is necessary both on the oil and the water side, as air pockets of any appreciable magnitude will result in buoyant forces which, in turn, will cause slight mechanical interferences which affect force readings and may be difficult to find.

Figure 14 shows the nature of the present variation of forces with change in working section pressure. It will be noted that the curve of increasing pressure on the first cycle diverges rather markedly from an average curve for the remainder; as this phenomenon always seems to recur, and it is assumed to be caused by the neoprene pressure seal, the practice now employed is to "exercise" the seal before starting runs by cycling the pressure in the working section several times.

The balance has been used for force measurements on hydrofoils, both fully wetted and cavitating, and measurements made to date indicate satisfactory operation. Figures 16 and 17 show typical results obtained from force measurements on hydrofoils with the modified balance.

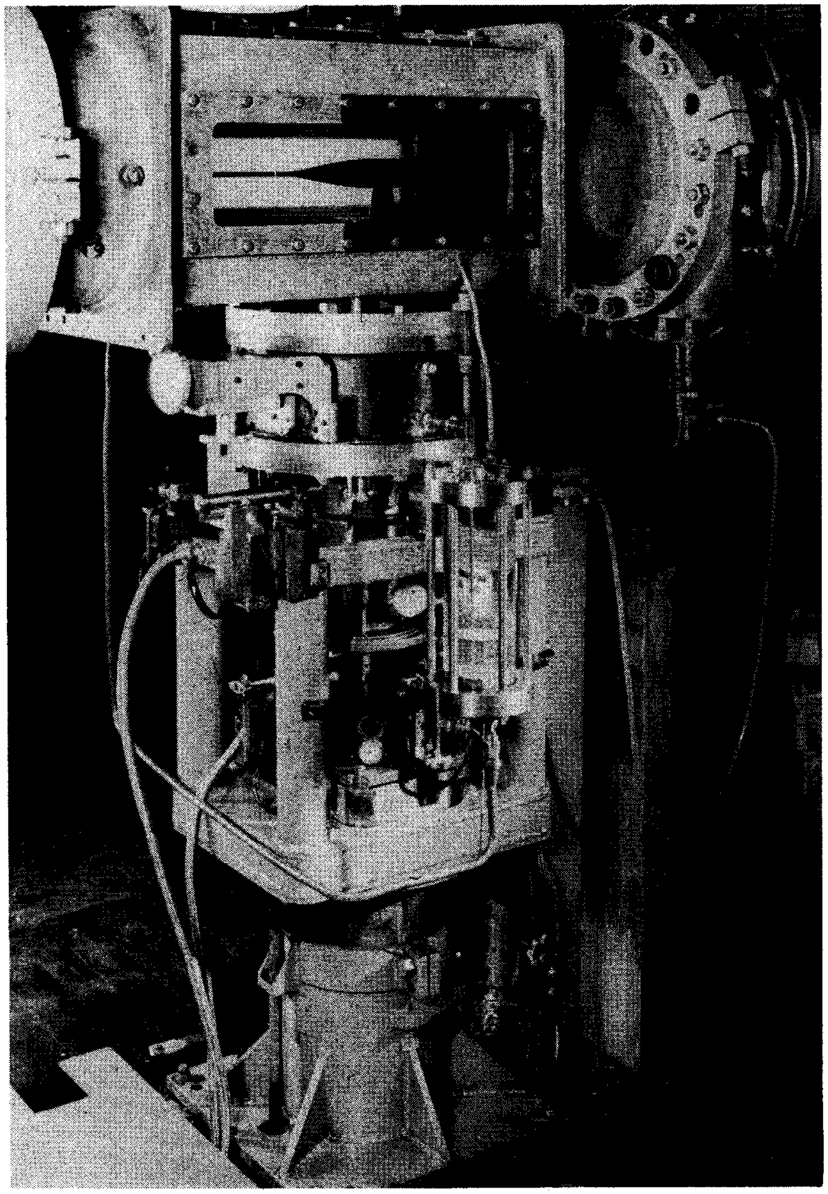

Fig. 13 - New balance installed vertically in working section

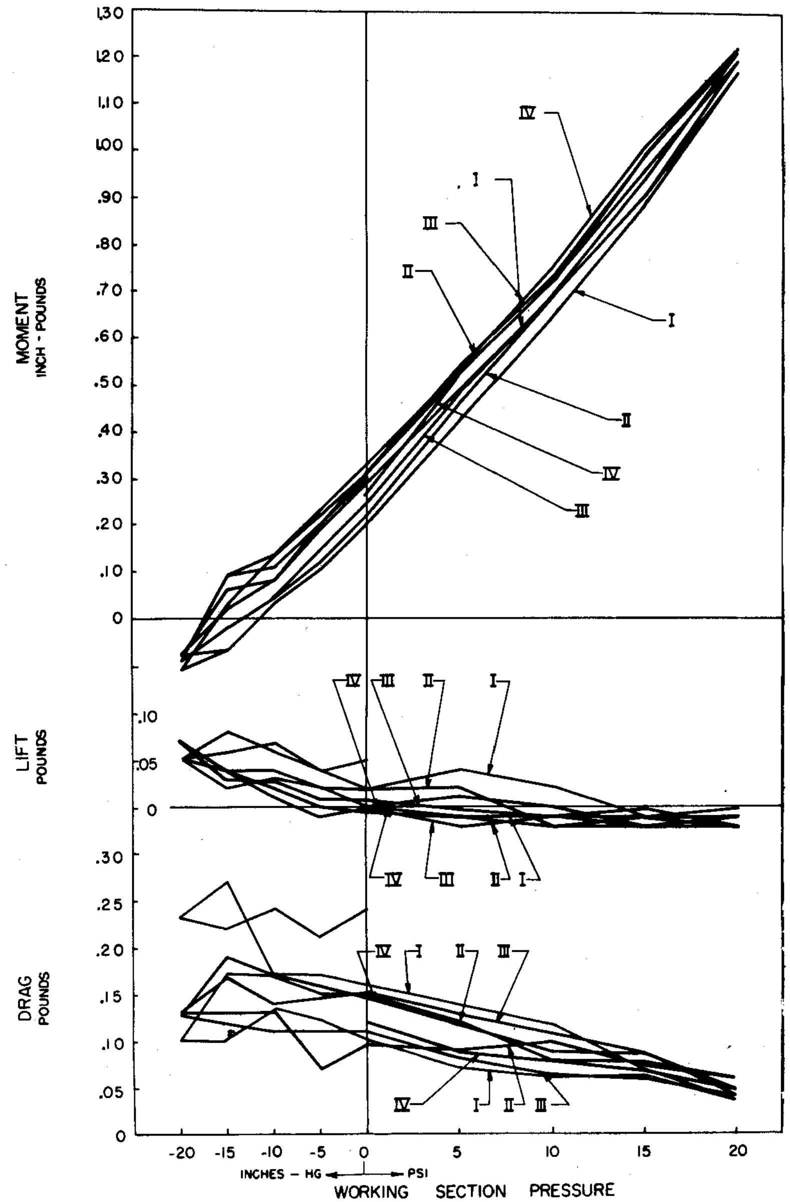

Fig. 14 - Calibration curves for pressure vs. lift, drag, and pitching moment for several cycles (I, II, III, IV)

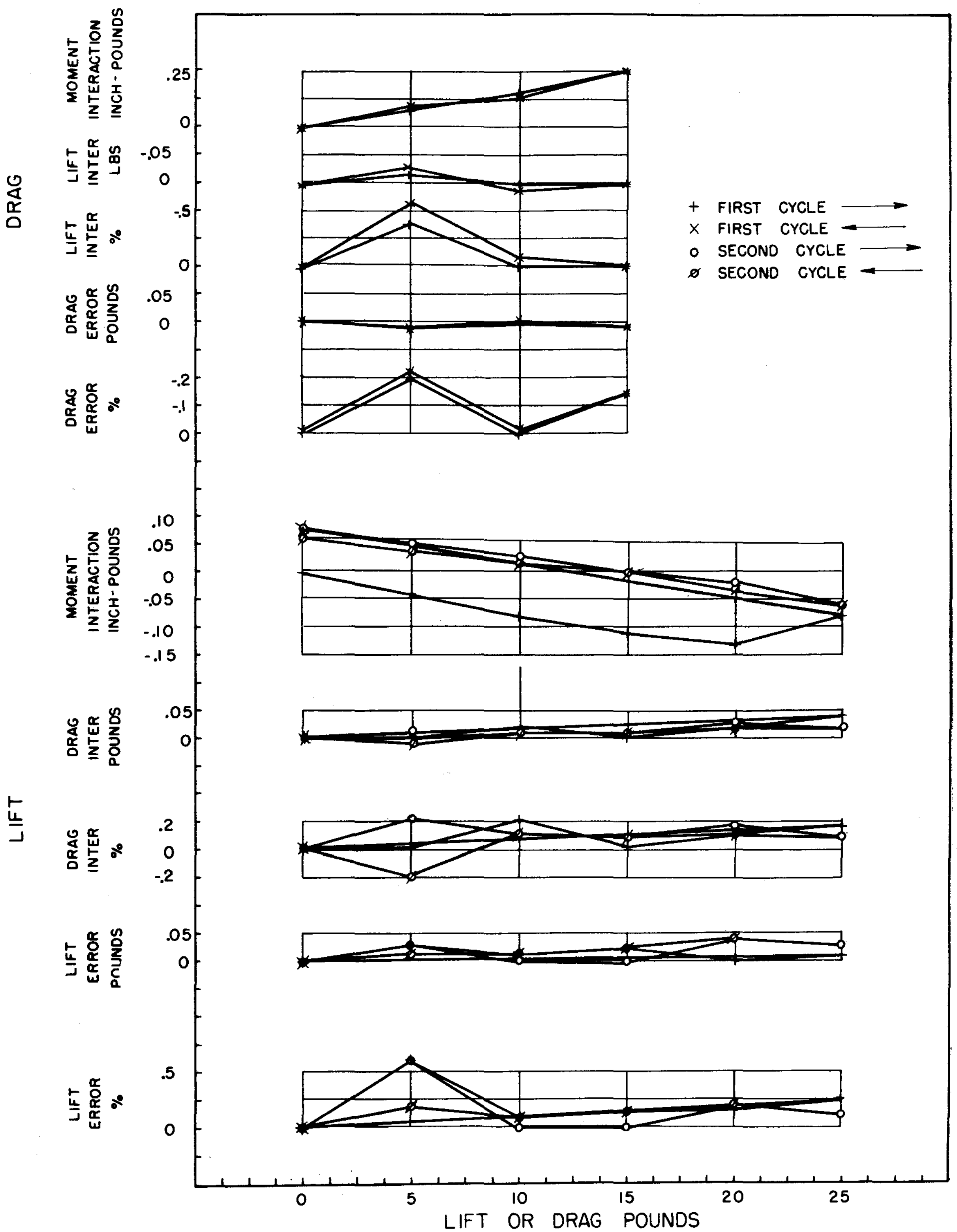

Fig. 15 - Static calibration curves for lift and drag.

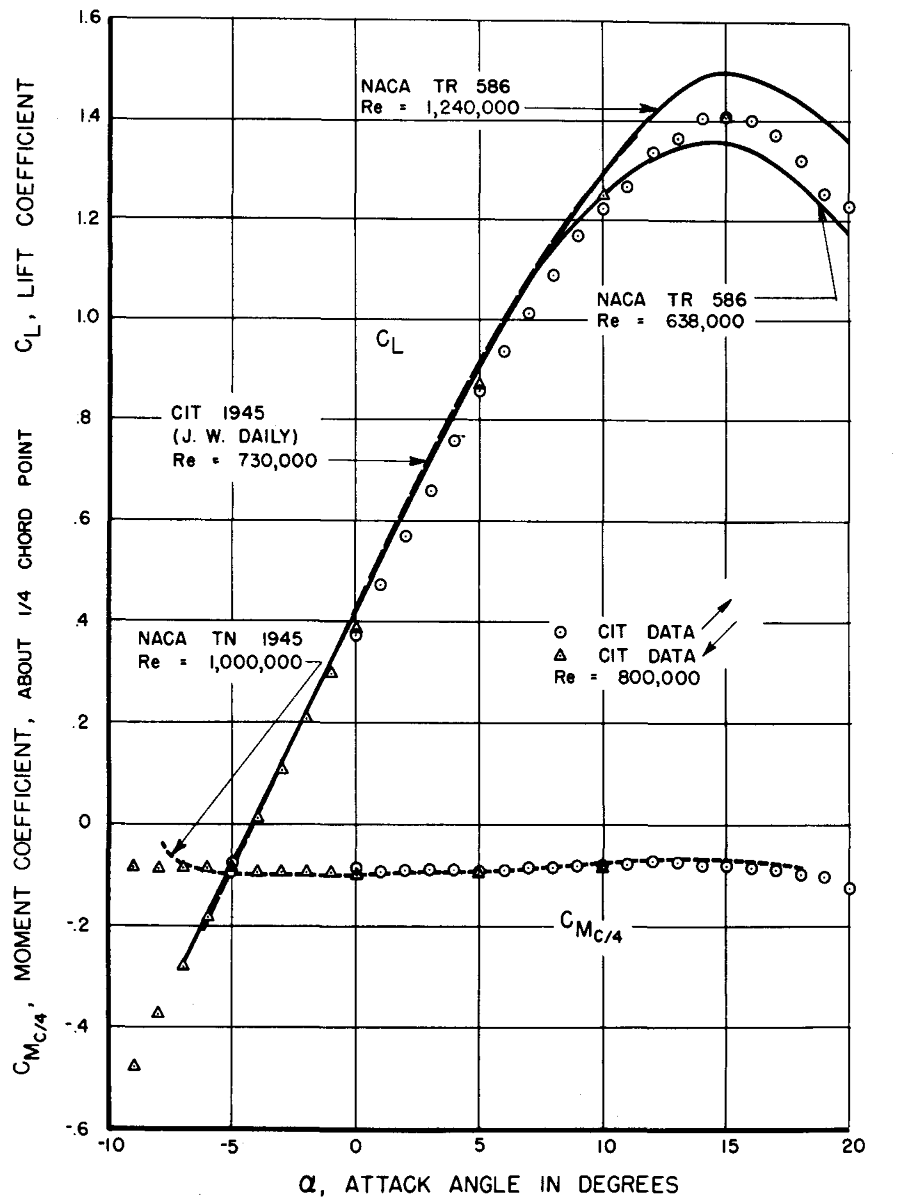

Fig. 16 - Typical force measurement results (noncavitating) - lift and moment coefficients for hydrofoil of NACA 4412 section. CIT hydrofoil data compared with NACA airfoil data.

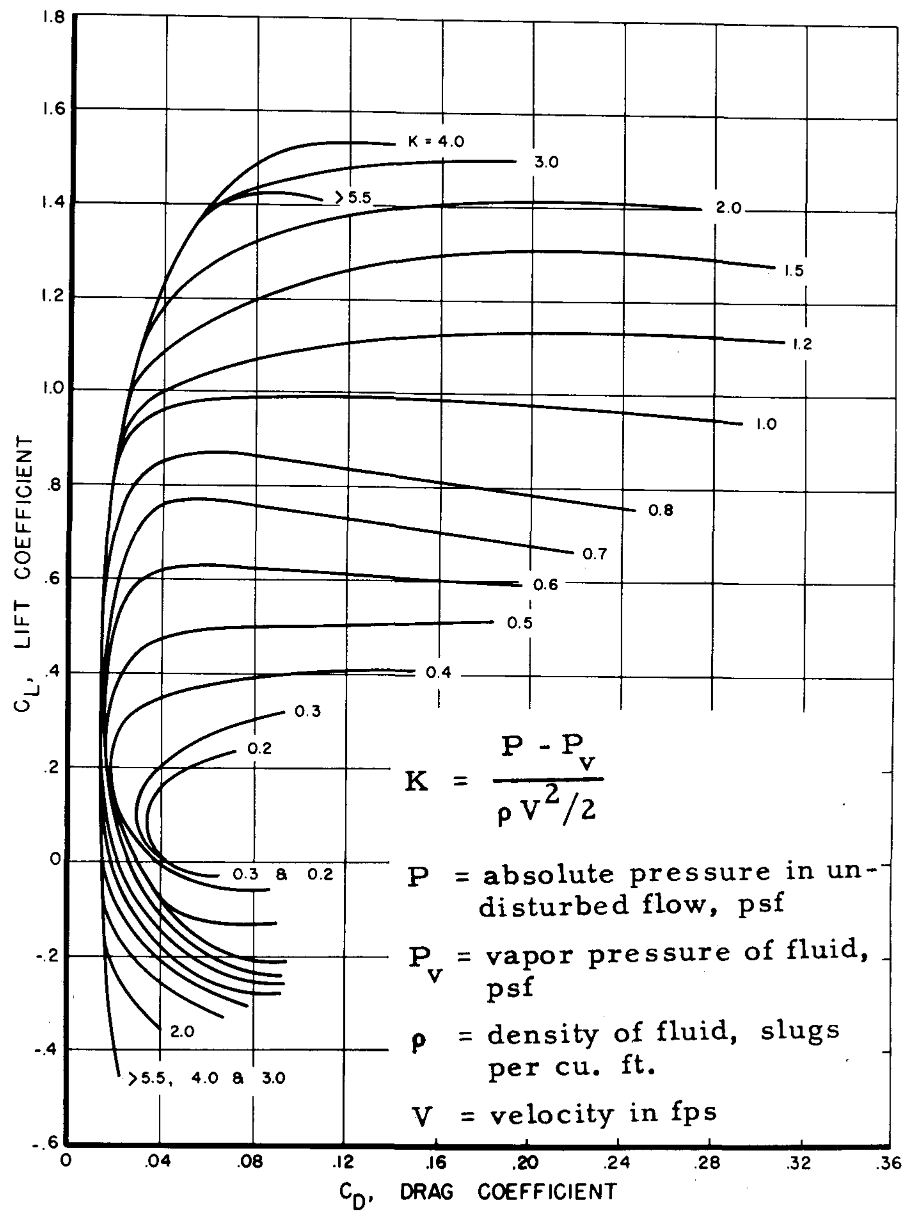

Fig. 17 - Typical force measurement results (cavitating) - lift and drag characteristics for hydrofoil of NACA 4412 section.

The drag and lift systems are both capable of measuring forces of 150 pounds to an accuracy of approximately ± .03 pound or about ± 0.02%.* Hydrofoil lift forces actually measured are up to the full range of the system; drag forces measured are of the order of 10 pounds maximum, resulting in accuracies of about ± 0.3% which are entirely adequate for the studies now being undertaken. If it were desired to increase the percentage accuracy of drag measurements to that attained with lift measurements, the drag range could be reduced to 1/10 of its present capacity.

V. CONCLUDING COMMENTS

The newly modified High Speed Water Tunnel force balance has proved to be a successful device which has made possible the accurate measurement of forces on cavitating and noncavitating hydrofoils. It is considered the most economical manner both in time and money in which a suitable force balance for use in the hydrofoil studies could be obtained when existing equipment was taken into account.

The old balance has been retained essentially intact and is still usable as such, but since the new balance will perform all the functions of the old one without the limitations and inconveniences involved in the internal moment measuring balances, it is expected that the new balance will be used for all force measurement work.

If an entirely new force measuring system were required for a facility such as the High Speed Water Tunnel, a parallelogram type balance with laminar flow "leakage seal"** and balancing seal, and employing hydraulic load cells with pressure gages similar to the present ones, would be recommended, time and funds permitting, (see Fig. 24 and paragraph D2, Appendix II). As a second choice, a balance of parallelogram geometry employing multi-element electric strain gage type force reading units, all placed in a pressure vessel filled with oil and employing an interface seal would be recommended.

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*Relative accuracy. Dead weights used are not known to be accurate to ± 0.02%.

**See paragraph C4 of Appendix II.

APPENDIX I.

DEFINITION OF FORCES AND MOMENTS

The original force balance in the High Speed Water Tunnel measured three components of the hydrodynamic forces acting on a model mounted on a vertical spindle, a drag force parallel to the flow, a yaw force (or cross force) normal to the flow, and a yawing moment about the axis of support.

If a hydrofoil were mounted on the old balance it would be necessary to orient the span vertically as shown in Fig. 18. In this position, rotating the hydrofoil about the support axis changes its angle of attack and the resultant moment would be a pitching moment which would be measured by the moment cell, the force normal to the flow would be lift and would be measured by the cross force cell, and the force parallel to the flow would be drag and would be measured by the drag cell.

All reference to forces and moments in this report, both for the old and new balances, will apply to the hydrofoil oriented as noted above and will be as indicated in Fig. 18.

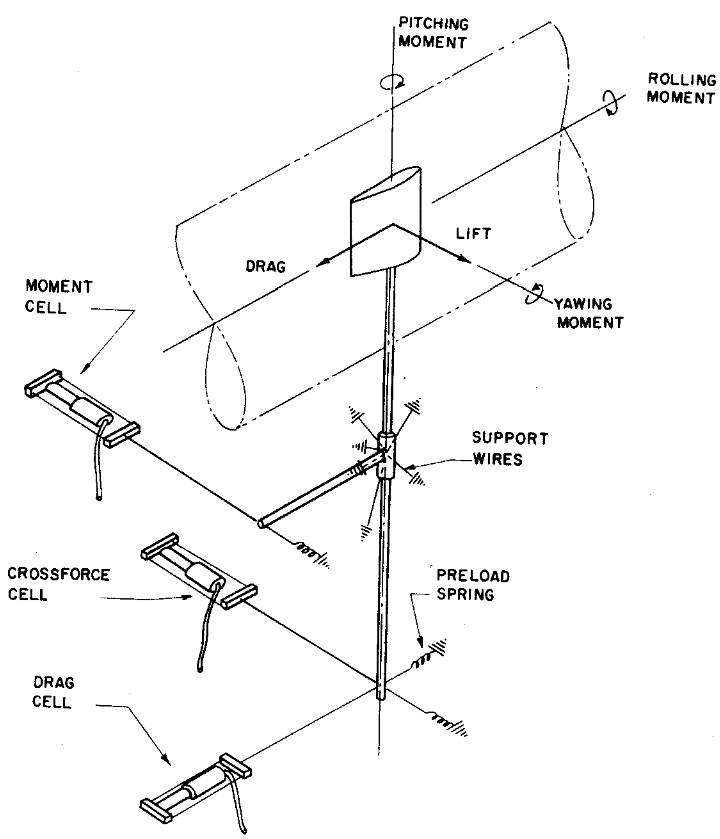

Fig. 18 - Schematic drawing of original High Speed Water Tunnel force balance showing force and moment conventions.

APPENDIX II.
COMMENTS ON WATER TUNNEL BALANCE DESIGN

A. Internal vs. External Balances

There is a current trend in wind tunnel balance design toward internal sting mounted force balances. This type has many advantages over the external type balance which apply to water tunnel applications as well, such as: (a) elimination of the pressure seal problem, (b) reduction of the problem of spindle deflection, (c) reduction of the shield interference problem, (d) great reduction in size and weight of balance over external type.

However the sting mounted internal force balance has certain drawbacks which preclude its use as a universal force measuring instrument in water tunnels, the chief one being that it does not lend itself to use with self-propelled models. This was the principle reason for the original selection of the external type balance design in the old High Speed Water Tunnel three-component balance. Although internal balances have their place in specialized water tunnel applications and in fact numerous internal force and moment balances have been built and successfully employed by the Hydrodynamics Laboratory, it was felt that such balances were impractical for hydrofoil force measurements because of the problem of attachment. Consideration was given in the design studies undertaken, therefore, only to external type balances.

B. Types of External Balances Considered

Both three- and six-component balances of various configurations were investigated. A basic premise in types of balances considered was that the geometry was to be such that each component would be measured separately and through one measurement only, not as the sum or difference of two or more measurements, primarily for reasons of accuracy, and secondarily, convenience. Thus the majority of platform and multiwire type balances was ruled out and consideration narrowed to:

(a) A six-component pyramidal type balance,

(b) A three-component parallelogram type balance.

These designs are discussed in paragraph D below.

Since the practicability of the new balance designs listed above depended upon whether a satisfactory seal could be devised for the nonpivoting type force table suspension used in these balances, studies were first made of pressure seals.

C. Pressure Seals

The problem of the pressure seal in a water tunnel balance is a difficult one because of the wide pressure range employed in tunnels used for cavitation work and because no leakage can be permitted. The High Speed Water Tunnel is operated from vapor pressure of cold water to about 100 psig, resulting in very large forces acting on the seal. Thus a seal sustaining an axial force on the order of 500 to 1000 lbs must be designed or arranged so that it does not induce any measurable force into the weighing system.

1. Reinforced Neoprene Seal

The seal employed in the existing High Speed Water Tunnel balance is a thick molded neoprene tube with metal reinforcing rings (see Fig. 7). The use of a rubberlike material for a pressure seal in this balance is dictated by the requirement that the seal be soft in torsion (rotation about its own axis) and frictionless. Required softness in all other directions (i.e., lift, drag, yawing and rolling moment) could be met with a metal bellows type seal. An undesirable characteristic of a neoprene seal, caused by the nonelastic nonhomogeneous nature of the material, is its tendency to move and rotate in all directions on change of pressure. These motions and the forces and moments produced by resistance to the motions are generally nonlinear and involve appreciable hysteresis effects. Tests of a seal of this type mounted in a parallelogram force table mock-up showed that although it was adequately soft in all directions when not under pressure, it required a force of about one pound to hold the force table in place on application of 50 psi pressure on the seal. This seal can be used in a pivotal type balance, such as the original High Speed Water Tunnel force balance, because the effect of the forces can be nearly eliminated from the weighing system by attaching the seal to the spindle as close as possible to the pivot center. The effects of the moments are small and can largely be taken into account through calibrations. The use of such a seal in a pyramidal or parallelogram type balance would, however, be impractical since the force sensing cells would directly measure the large spurious seal forces.

2. Pressure Vessel Enclosing Balance

The alternative to employing a pressure seal is to eliminate it through the use of a pressure vessel encasing the entire balance and pressurizing it to working section pressure, as is done in some wind tunnel balances. The pressure vessel could be filled with (a) tunnel water, (b) oil, or (c) air; with oil or air a thin neoprene diaphragm type interface seal would be required to separate the tunnel water from the other fluid. Oil was considered the best fluid for the purpose, as it is incompressible, noncorrosive, and has a low vapor pressure; water would impose limitations on materials and the use of electric elements and would contain troublesome sediment; air would necessitate the use of large supply tanks and pumps to permit rapid and frequent pressure changes. The size and weight of the pressure vessel, the problem of making it readily removable for servicing of the balance, the added complexity of installing balancing pistons or using differential pressure gages to eliminate the effect of water tunnel pressure on the hydraulic load cells, and a natural reluctance to change to an enclosed balance because of past experience with the operational advantages of the open construction of the High Speed Water Tunnel balance led to discarding this scheme for this particular balance.

It should be pointed out that in the balance modification actually adopted, described in paragraph IV of the body of this report, only the new parallelogram mounted force table, which does not require accessibility, was enclosed in the oil-filled pressure vessel, whereas parts which require attention such as load cells, preload springs, and compensators, are completely open and accessible. Such would not be the case in the completely enclosed balance described above. As indicated in paragraph V of the body of this report, use of a pressure vessel for completely enclosing the balance would be considered in the design of a new force balance wherein strain gage type force sensing elements were acceptable.

3. Mercury Seal

Another sealing arrangement investigated was a mercury seal, shown in Fig. 19, which is in effect a number of U tube mercury manometers in series, arranged as an annular labyrinth wherein the working section pressure is sustained by the sum of the difference in lengths of the mercury columns. It will be noted that the width of the mercury column varies

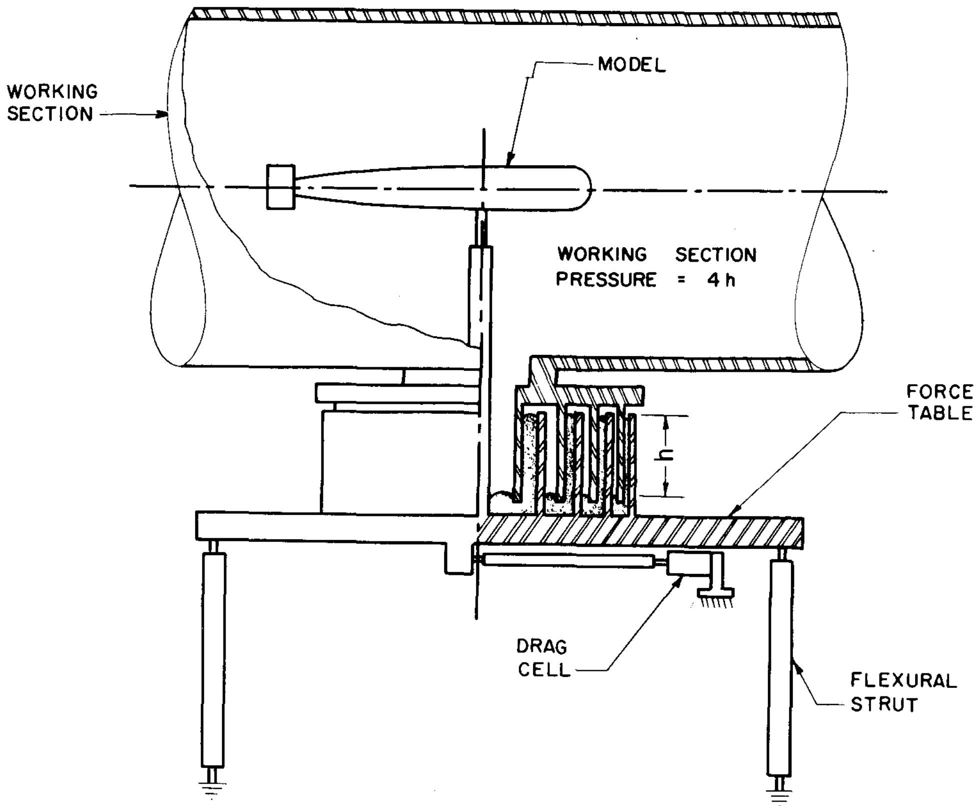

Fig. 19 - Proposed mercury column pressure seal.

inversely with distance from center of the balance. Although this seal should be satisfactory for low pressures, it was considered impractical for the balance in question for reasons of size, weight, difficulty of fabrication, and necessity for mounting in a vertical position.

4. Laminar Flow Seal.

Still another type of seal was investigated and developed experimentally which would make a pyramidal or parallelogram type balance feasible without the objectionable features of enclosing the entire balance in a pressure vessel. This was a laminar flow type "leakage seal" shown in Figs. 20a and 20b. In this type of seal an interface diaphragm is employed to separate the water from the "leakage" oil. Oil is supplied at water tunnel pressure to chamber "A", Fig. 20a, to balance the water pressure on the other side of the interface seal. The oil is permitted to leak radially to atmosphere through a small clearance gap between parallel surfaces, one attached to the force table and the other to ground. For pressures below atmospheric, the oil flow through the leakage seal is reversed. The interface seal is so constructed as to be capable of sustaining a small differential pressure without damage or

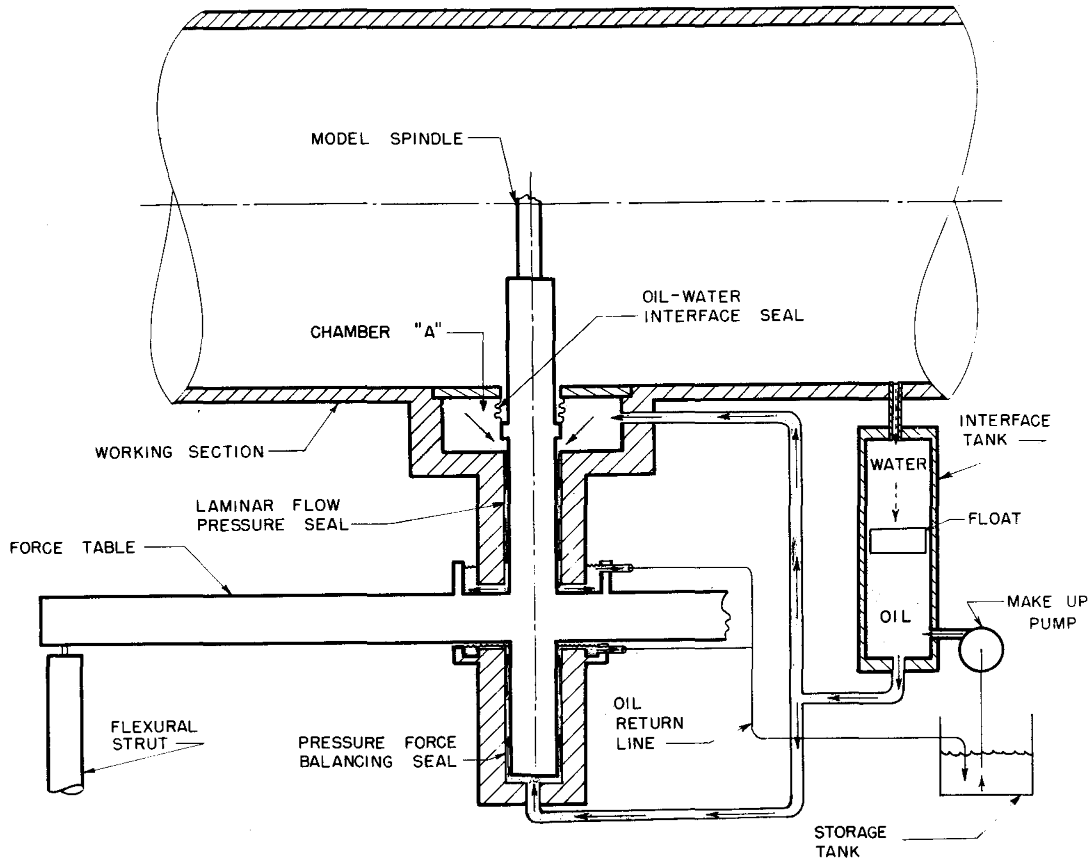

Fig. 20~~a~~b - ~~Radial~~ AXIAL laminar flow pressure seal schematic.

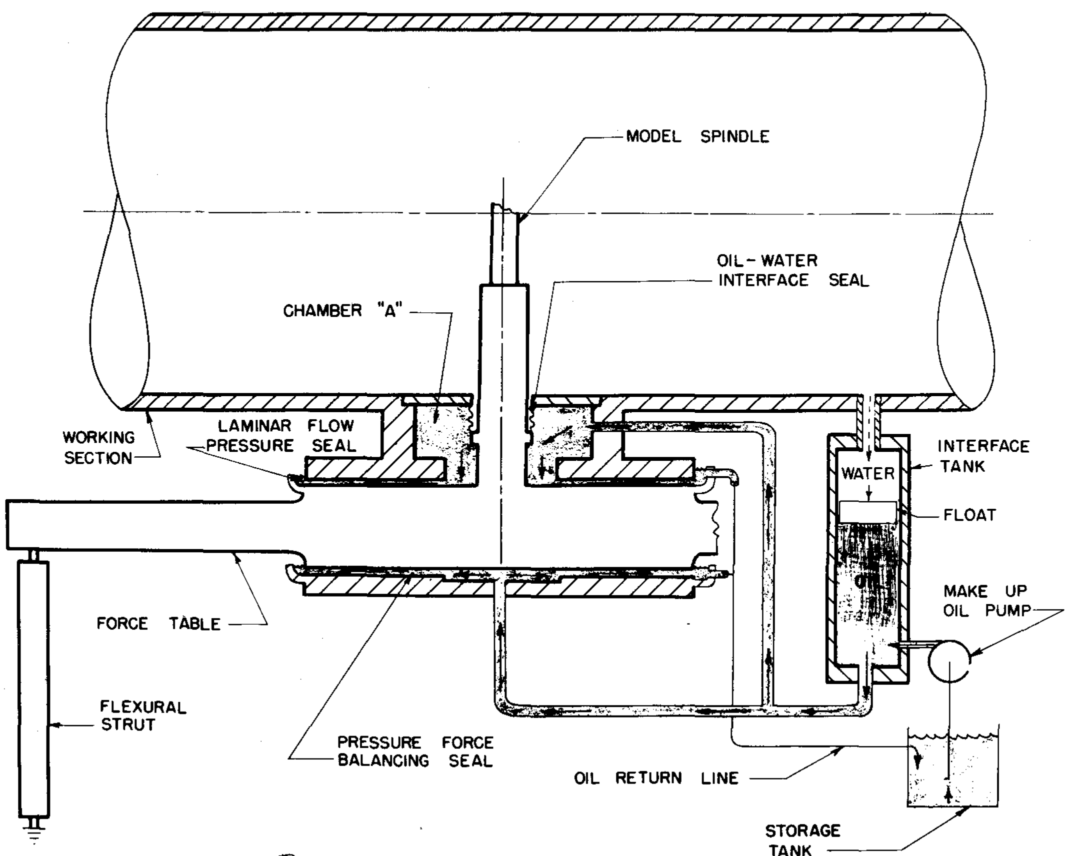

Fig. 20~~b~~a - ~~Axial~~ RADIAL laminar flow pressure seal schematic.

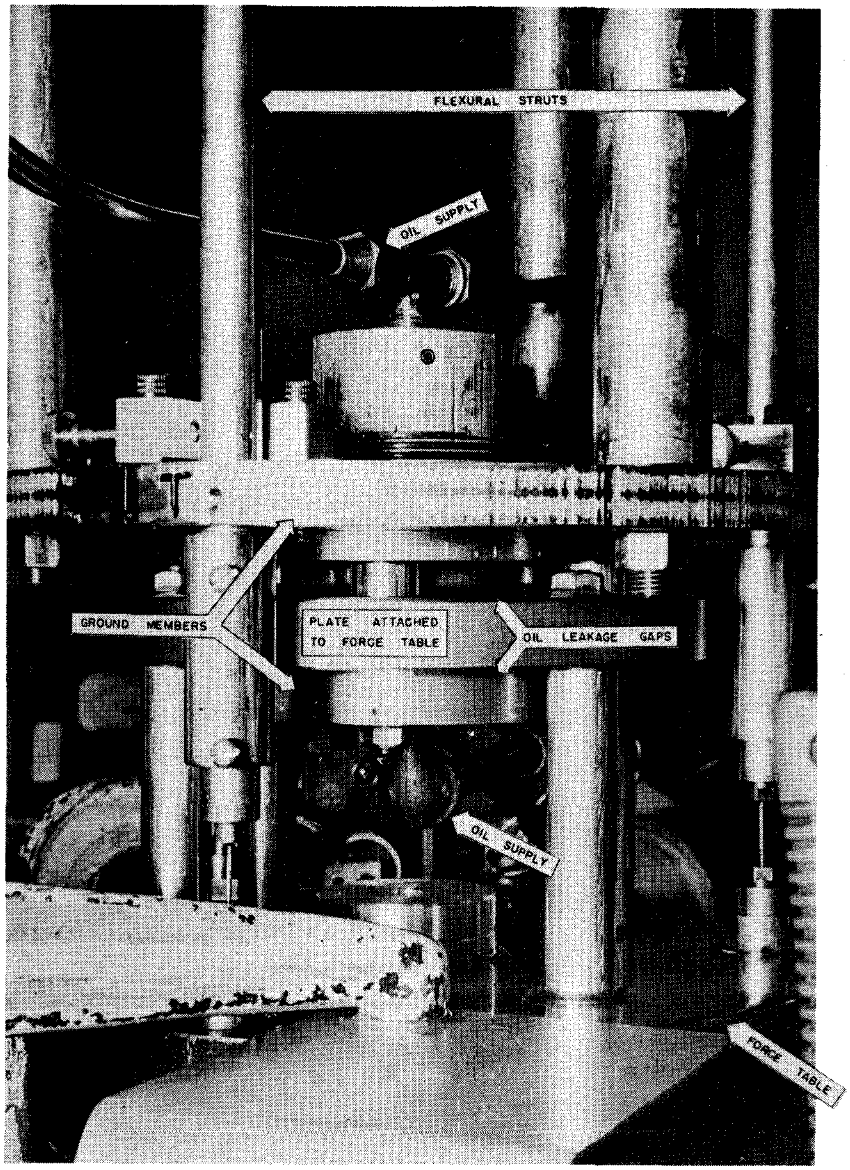

Fig. 21 - Radial laminar flow seal test setup.

appreciably affecting the force balance readings. In the experimental setup (see Fig. 21) a second leakage gap was used to balance the large axial pressure force exerted on the force table; this would also be highly desirable in the force balance application of the laminar flow seal. An axial laminar flow seal was also tested (see Fig. 20b); it has the advantage over the radial flow arrangement of having a much smaller area on which pressure acts and that increasing the length of the leakage path does not appreciably affect the axial force. However, difficulty in alignment proved too great in the test setup and it was abandoned in favor of the radial type seal.

It would appear that the axial flow leakage seal has considerable merit and should prove feasible with a high viscosity leakage oil which would permit a radial clearance on the order of 0.005" - 0.007" in lieu of 0.002" - 0.003" used in the experimental setup. Either this type or the radial flow seal should prove stable as long as the gap between the plates never becomes zero. In tests of the radial flow seal, several gaps were used and fluids of various viscosities tried, from water to SAE 30 motor oil. It was concluded that with water, clearance gaps necessary for laminar flow with a leakage path of reasonable length were prohibitively small. Results obtained with the radial laminar flow seal using SAE 20 to 30 oils, shown in Figs. 22a and b, indicated that for a seal of practical dimensions and alignment a small unbalanced radial force is possible over an appreciable pressure range and is largely independent of small radial and/or axial force table movements.

D. Investigation of New Force Balance Designs

1. Pyramidal Type Six-Component Balance

At the conclusion of successful testing of the radial "leakage seal" the preliminary design of the two balances requiring a seal of this character was undertaken. Figure 23 shows a pyramidal type six-component balance which was considered. It employs six hydraulic force sensing cells which measure the six components independently. This balance was discarded for reasons of size complexity and cost; although a six-component balance would be desirable at times, past experience has indicated that a balance measuring three components independently together with special purpose internal balances would meet most of the High Speed Water Tunnel's requirements.

2. Parallelogram Type Three-Component Balance

Next a three-component parallelogram type balance, illustrated in Fig. 24 was studied. The force table of this balance is suspended on three vertical flexural struts which serve to locate the table and allow it freedom of motion in the drag, lift, and pitching moment directions only. Drag or lift forces are transmitted to the force sensing cells through long flexural struts which offer little resistance to motion in a direction normal to their axes or to rotation of the force table. Pitching moment is transmitted to a pair of parallel flexural struts, through a moment transmitting cylinder, one attached to ground and the other to ground through a force sensing cell.

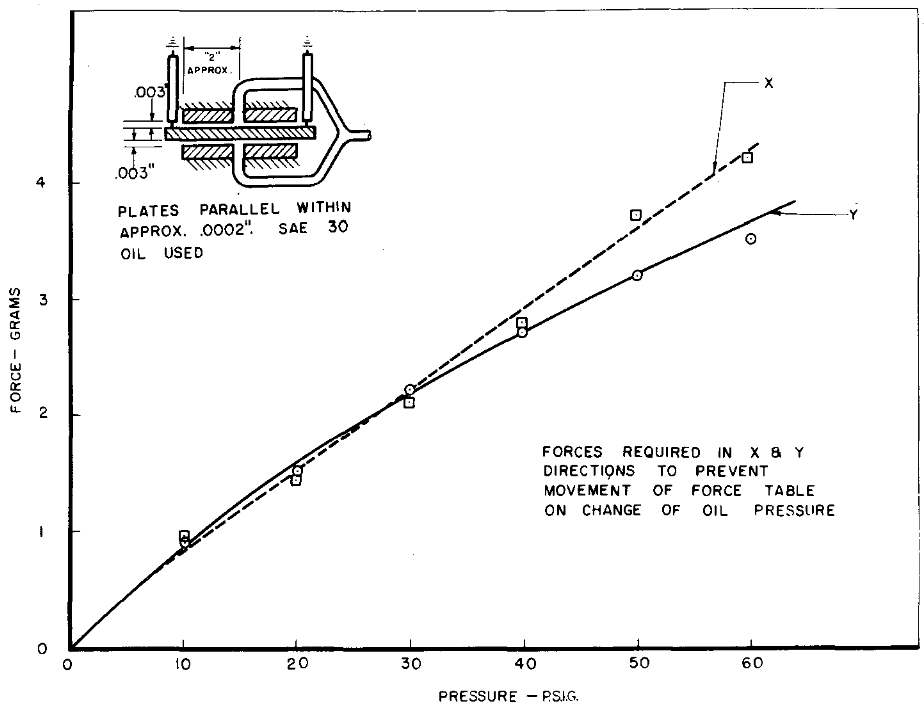

Fig. 22a - Unbalanced radial forces in radial laminar flow "leakage seal" - plates parallel.

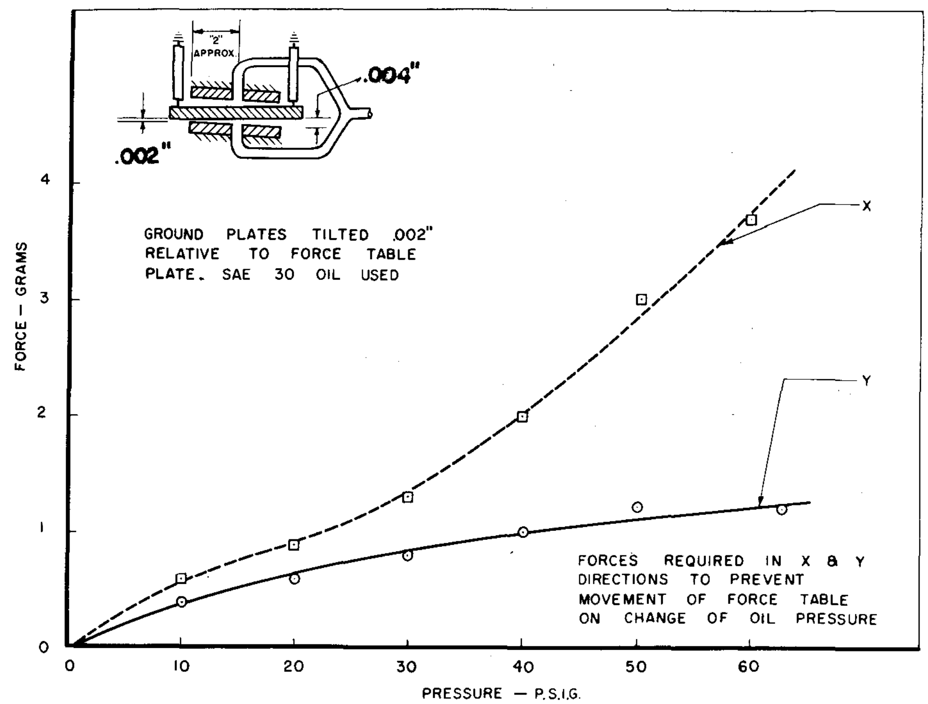

Fig. 22b - Unbalanced radial forces in radial laminar flow "leakage seal" - plates not parallel.

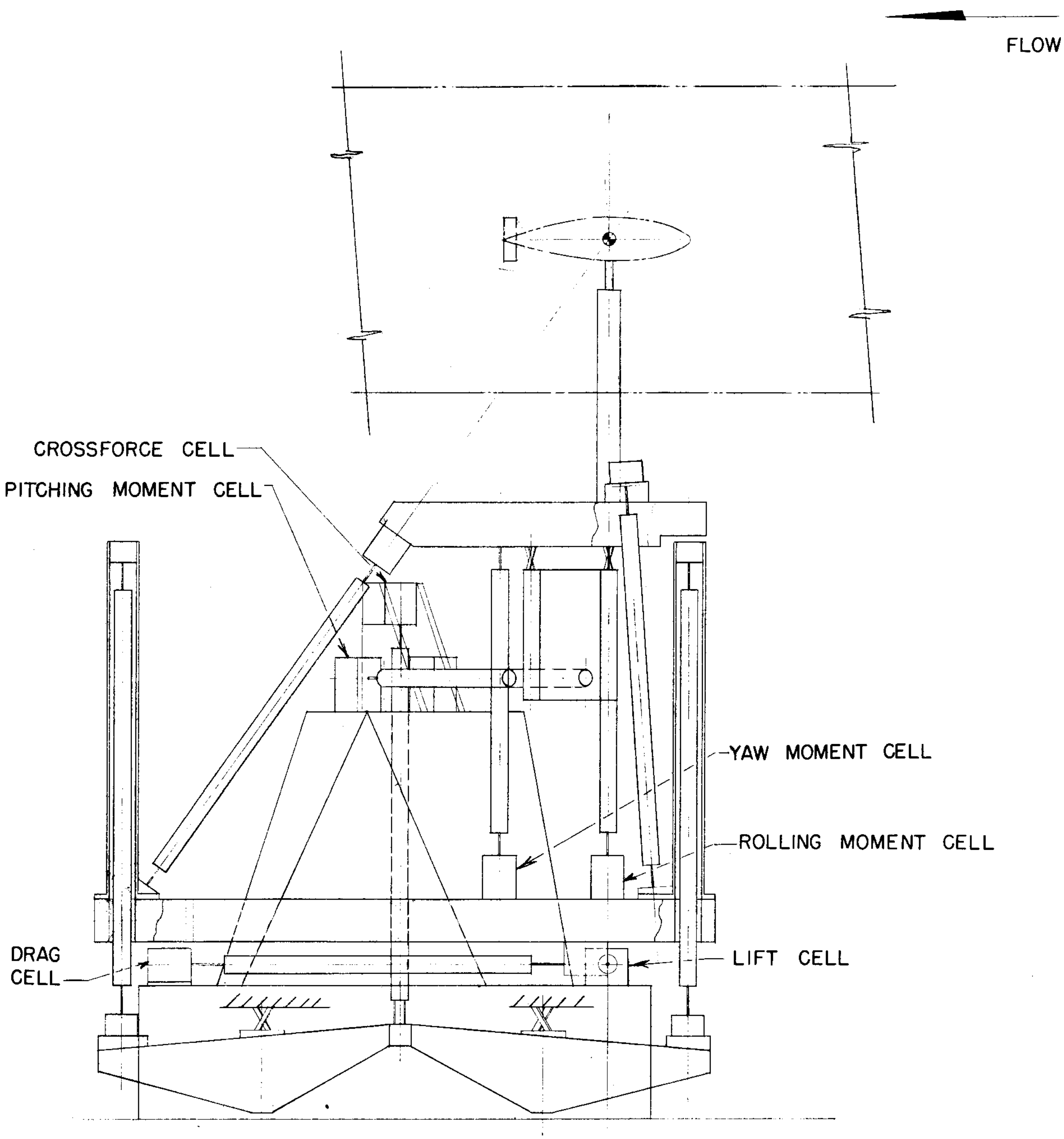

Fig. 23 - Six-component force balance proposal.

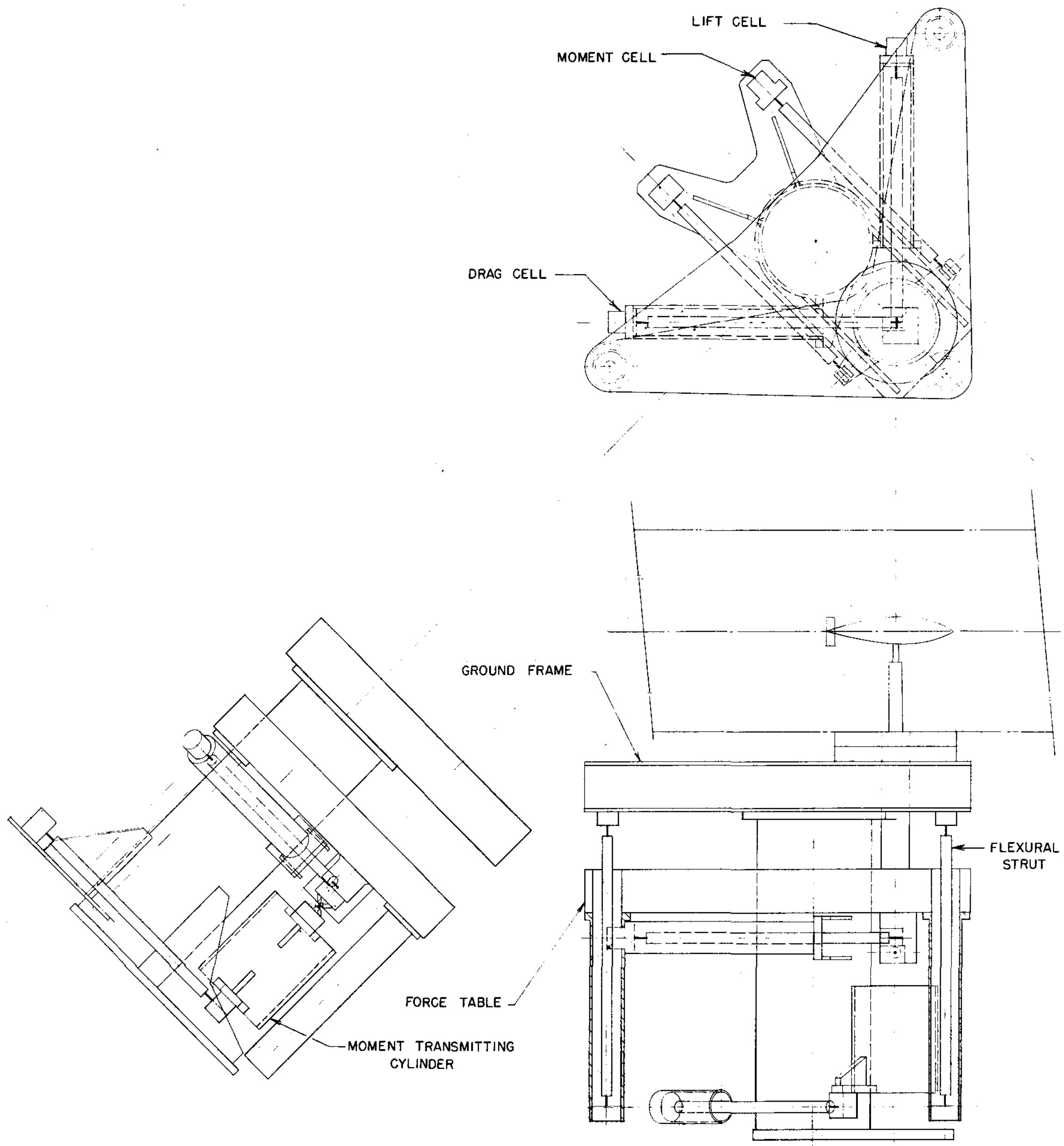

Fig. 24 - Parallelogram type three-component force balance proposal.

Thus a moment is measured as the force felt by this cell multiplied by the distance between the two moment transmitting struts. The moment measuring system offers little resistance to motion in the drag and lift directions, making possible the measurement of the three desired components independently.

Figure 25 shows the arrangement of the radial laminar flow type seal in this balance. A balancing seal is provided to relieve the vertical flexural struts which mount the force table from carrying the pressure load. If this were not done these vertical flexural struts would have to be very long

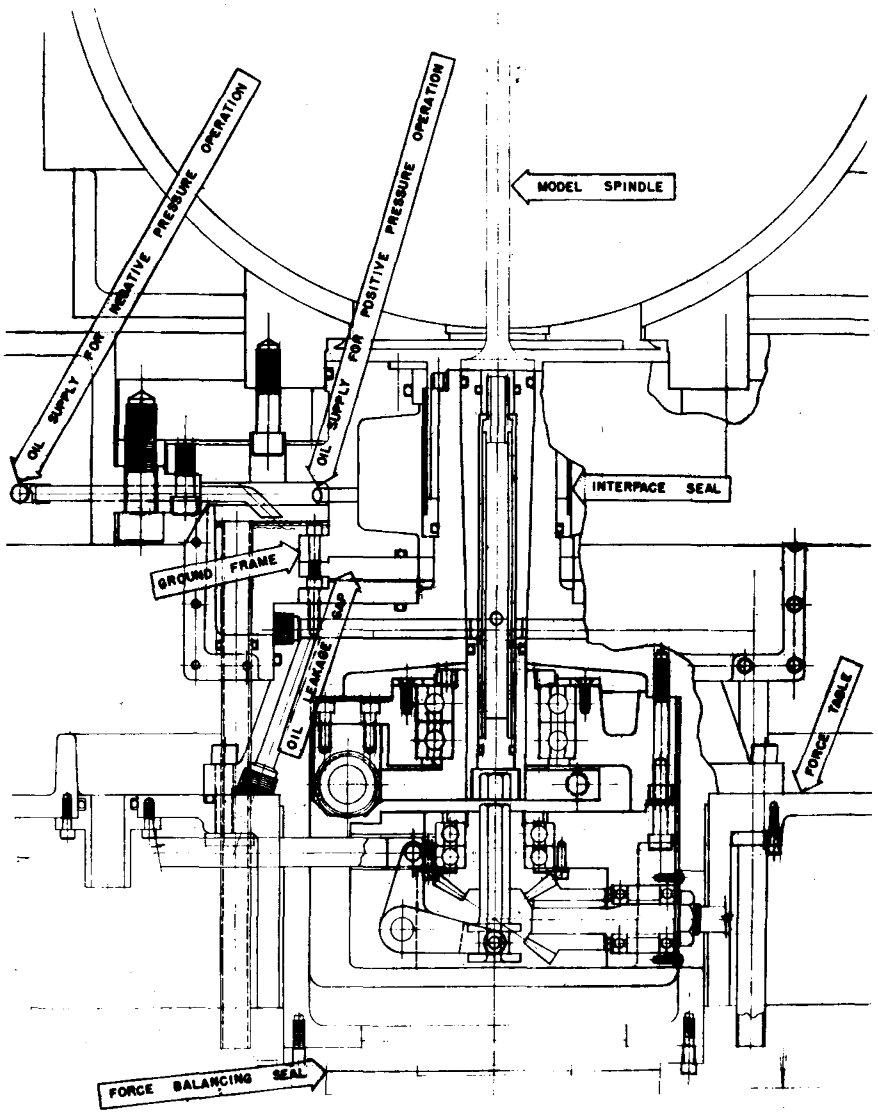

Fig. 25 - Laminar flow "leakage seal" in proposed parallelogram type three-component force balance.

to keep the horizontal component of their axial load smaller than the least count of the balance when the table moved approximately 0.003" from center due to force sensing cell leakage and mechanical deflections. The design of this balance was carried through the general arrangement stage to the point where cost and time for construction could be estimated. It was felt that this was a feasible design with much to recommend it.

A lower cost balance and lower cost read out equipment (with correspondingly reduced accuracy) might be built by enclosing the balance shown in Fig. 24 in an oil filled pressure vessel and substituting electric strain gage type force sensing cells (such as Statham dynamometers) for the hydraulic cells. The accuracy of such a balance, when measuring forces well under the capacity of the balance, could be appreciably improved through the use of two or more Statham units to cover the range for each component instead of one. Such units could be mechanically switched in or out.

E. Investigation of Modifications to Original Balance

Next, modifications to the existing balance were studied to determine whether they might be accomplished more quickly and economically than the construction of an entirely new balance.

1. Strut Type Model Mount

The first modification investigated consisted of hinging the model on the spindle so that it could rotate in yaw and then preventing such rotation by attaching to the model some distance aft of the spindle the top of a hinged strut, the lower end of which is attached to the spindle through a force sensing element, as illustrated in Fig. 26. Thus the force element measures yawing moment and permits correction of drag force readings. Although this modification could have been more readily accomplished than either the modification finally decided upon or a new balance, it was felt that it would have resulted in inadequate rigidity of model support, causing particular difficulties in cavitating flow, besides being difficult to accomplish for both yawing and rolling moments.

2. Parallelogram Mounted Force Table Appendage

This was the balance modification actually accomplished and is fully described in paragraph IV C of the body of this report.

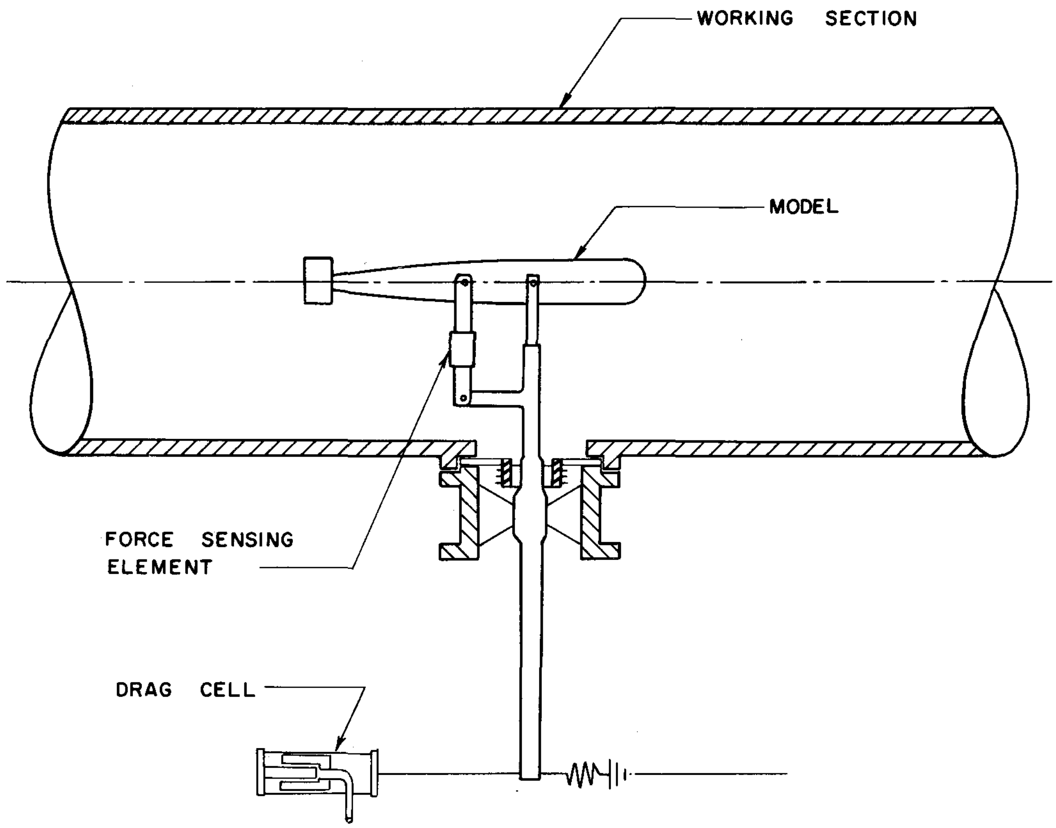

Fig. 26 - Two strut model mount for moment measurement.